THE ORE MAGMAS

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A SERIES OF

ESSAYS ON ORE DEPOSITION

BY

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FOREWORD

This volume differs somewhat from most books on ore deposits in being essentially a record of my own personal studies and opinions as to the origin of ore deposits, a subject of vast scientific and practical interest. Only here and there have I deviated from my personal experience to dwell upon a few instances of the work of others, where this seemed advisable to fill out my story.

These observations and conclusions, then, represent the gist of thirty years' study of ore deposits, mainly in the field; at least they represent what I consider the most fundamental principles underlying the science. I have written them from one motive alone: the setting forth of my experiences and opinions, for such help as they may be to others.

JOSIAH EDWARD SPURR.

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SYNOPSES OF CHAPTERS

To provide a brief conspectus of the arguments running through this work, which will be a help to the reader in summing up the purport of these essays, either before, after, or during the reading of the book, the following synopses have been prepared. In form and general purpose they are similar to the synopses of a course of lectures, which are often prepared and given out by a lecturer covering a college course.

CHAPTER I

The Origin of Ore Magmas or Solutions: Veindikes

WHATEVER will explain the close association, in veins, of quartz and metals will illuminate ore deposition. In 1908, I observed in Alaska that quartz veins carrying gold could be traced into pegmatites and aplites consisting of quartz and feldspar. These passed into various types of hornblende-feldspar rocks, and all these varieties I accounted for (and still do) by what is called *magmatic differentiation*. Assuming this magmatic differentiation origin for veins and rocks, I understood for the first time the association of quartz and gold, both being results of extreme differentiation. Therefore, there is no hard and fast line between the magma solutions which have deposited alaskites and those which deposited the related auriferous quartz veins—both are magma solutions.

Water must be present in all magmas, which are fluid more on account of solution than heat, important though the latter is. On rock solidification, water is expelled. The gradation of granites and alaskites into pegmatites shows that the pegmatite magma is a variation or residuum of the granite magma; and the freedom of segregation of like minerals in the pegmatites proves that the pegmatite magma contains more water and other mobile elements than does the granite magma. Rare minerals are thus frequently concentrated in pegmatites—such as apatite, topaz, and beryl.

Igneous rocks contain metals—like gold and copper—universally distributed, perhaps as silicates; the metals also occur in rocks as oxides and sulphides, such as magnetite, ilmenite, pyrite, probably chalcopyrite, and perhaps molybdenite. In pegmatites metallic minerals are also present—pyrite, chalcopyrite, molybdenite, and gold are frequently found. Such pegmatites may show all gradations from a quartz-feldspar to a pure quartz rock.

It is difficult to choose between the words "dike" and "vein" for these types. Therefore, I propose to call these borderland types "vein-dikes"; they are intrusive, but the intrusive magma differed from that typical of the usual igneous rock.

Scheerer pointed out, as early as 1846, the dependence of granitic magma solutions on contained water. In 1884, Lehmann confirmed this view and argued that pegmatites were injections, and that the quartz veins or dikes transitional into the pegmatites must have had a similar origin. Howitt, in 1887, came to the same conclusion in Australia. In the United States, Lane in 1894, and Crosby and Fuller in 1897, maintained that quartz "veins" with an obvious relation to pegmatites were the end product of magmatic differentiation.

More difficultly came the acknowledgment that those quartz veins which contained metallic minerals had this origin by magmatic differentiation. Howitt did not acknowledge it for the Australian types. I published this conclusion in 1898, for the Yukon gold-quartz veins (that they were the end products of granitic magma differentiation), and a little later in the same year Hussak described an auriferous quartz vein in Brazil as an intrusive ultra-siliceous granitic dike.

Let us remember that all magmas—even rock magmas—are solutions.

The theory of the formation of mineral veins by emanations from volcanic and other igneous rocks dates back at least to Elie de Beaumont in 1847; but this is not the magmatic-differentiation theory which I am propounding. The magmatic-differentiation theory for auriferous quartz veins was, indeed, propounded before me, by Thomas Belt, in 1867 and 1871. He noted the transition from granite to quartz veins, and believed this to be the origin of gold-quartz veins in general.

In the Silver Peak district, Nevada, I found further proof of the transition from alaskite to gold-quartz veins.

This differentiation of granitic or alaskitic magmas into gold-quartz veins as final end products must take place at a depth of several miles—my impression is that it is many miles in some cases. As to temperature, artificial formation of granitic minerals, and other criteria, indicate that granites and pegmatitic granites crystallized between 575 and 800° C.; while the pegmatites and related (pegmatitic) quartz veins crystallized from 575° to a somewhat lower temperature.

Metallic sulphides in pegmatites are usually not important commer-

cially; but in quartz veins of close pegmatitic affiliation the metallic sulphides are more frequently commercially valuable. The commonest ores which I have seen of this kind are those of tungsten; tin also commonly occurs in veins or veindikes of this type.

Closely allied to these, but not so closely allied to pegmatites, is a certain type of quartz vein carrying free gold, auriferous pyrite, and other sulphides: such as those I described in Alaska and at Silver Peak, and those of California, Canada, the Appalachians, and Australia. These are "free-milling" (i. e., easily amalgamated) medium to low-grade ores; and they occur only in regions which have undergone deep erosion.

These ores are often true veindikes, and have intruded their country rock, pressing the fissure walls apart by their inherent or "telluric" pressure. They assume lenticular forms when formed at great depths; formed at somewhat lesser depths, they have the more tabular vein form, and contain typically rather more gold.

CHAPTER II

The Mode of Injection of Mineral Veins, and the Nature of Ore Magmas or Solutions

THE PROBLEMS OF INTRUSION of igneous rocks and mineral veindikes are important. According to the old school of economic geology, the main problem was to find out the origin of the openings in the rocks, which had been later filled by ore. We do find openings in the rocks underground, in mines; and they often contain water, but show no sign of being in process of filling by veins. That waters have circulated along these rock fissures for sometimes demonstrably vast geologic periods without the beginning of cementation to form veins or ores is a striking fact opposed to the popular theory of ore deposition, as, for example, that generally held for the Mississippi Valley lead-zinc ores. I have personally examined many thousands of miles of mine workings; and in no case have I seen any vein in process of formation. Primary veins (by which I mean to exclude superficial enrichment and reworking processes) must, therefore, be formed under conditions not accessible to mines, either because they are formed at too great depths or at too high temperatures.

Let us consider the Silver Peak gold-quartz veins. They occur as a zone of lenses; and these lenses are not due to a crushing of the quartz, which shows no evidence of such pressure. No open cavities of the great size occupied by some of these quartz lenses could have existed; therefore, the quartz must have been intruded under its own inherent pressure. What was the nature of this inherent pressure?

The shaly country rock near the quartz intrusions is intricately injected and replaced by quartz; nevertheless, certain phenomena indicate that the quartz magma solutions were not so very highly aqueous. I suspect that some of the schistosity in the wall rocks may have been due to the shearing action of the intruding magma. The intrusive origin of certain gold-quartz veins in the Appalachian states was suggested by Graton in the year after I ascribed a similar origin to the Silver Peak gold-quartz veins.

At Herb Lake, in Manitoba, I have studied molybdenite-bearing quartz veindikes transitional into pegmatites. In these veindikes there is frequently a noticeable difference in age between the quartz and the feldspar, and considerable segregation of these minerals (as well as muscovite) one from another was accordingly effected. The molybdenite-bearing veindikes carry a little gold. The general order of crystallization is: first, orthoclase, followed by muscovite, and last quartz.

Related to these molybdenite-gold-bearing veindikes are certain gold-quartz veins, a few miles away. These form persistent veins, characterized by a series of bulges and pinches, like a string of lenticular beads. These veins carry black tourmaline and some muscovite; and I concluded that they were almost a variation of the molybdenite-gold-bearing veindikes; they carry free gold. Most of the metallic minerals are deposited along parallel fractures later than the quartz of the veins; this is true of the free gold, and also of a considerable amount of arsenopyrite (with a little copper pyrite). This is the familiar "ribbon structure" so often found in gold-quartz veins of deep-seated origin. Such auriferous arsenopyrite as here occurs along fractures in the quartz may evidently occur in a fissure by itself, as a massive sulphide vein; and, to be sure, at Silver Peak, in Nevada, and elsewhere, we find such massive auriferous arsenopyrite veins.

At Beaver Lake, Canada, in the same auriferous belt as Herb Lake, are also to be found lenticular auriferous quartz veins in pre-Cambrian schist. Copper pyrite is perhaps the predominating sulphide in these veins; and in the general region are very large deposits of sulphides, with very little quartz.

The Mandy mine, at Schist Lake, is such a sulphide lens in schist; it consists principally of massive chalcopyrite and blende, with very little quartz. The following sequence of deposition is indicated: 1, A very unimportant amount of coarse quartz and pyrite; 2, massive fine-grained blende, containing many streaks of cupriferous pyrite, the two intimately drawn out and interstreaked by flow as if in a stiff paste; 3, high-grade chalcopyrite, with streaks and bands of blende, evidently the result of flow.

Microscopic sections show that the ore has not been crushed or strained.

Therefore, both main periods of ore deposition, first of blende and later of chalcopyrite, were intrusions of plastic sulphides. If intrusive, then, why is the orebody an apparently isolated lens? Why do not igneous rocks occur in these apparently isolated lenses?

Last of all the ore stages in the Mandy mine is a little blende and much pyrite, with about 50 per cent quartz; this evidently was deposited from a thinner and more aqueous solution.

A few miles from the Mandy lies the Flin Flon orebody, about 2,000 feet long and 100 or 200 feet wide, consisting of massive sulphides, replacing in all stages a greenstone schist. The principal values are in gold, silver, and copper. The Flin Flon orebody is thought to represent the same general conditions of deposition as the last stage of the Mandy. Other large masses of sulphides occur in the region, mainly pyrite and pyrrhotite, without commercial value; and they, like the Flin Flon ore, have evidently formed by replacement. Sulphide bodies of this type are not veindikes: they were deposited by solutions heavily charged with iron, sulphur, and silica, with, at some stages, a certain amount of gold, silver, copper, lead, and zinc. These solutions were apparently residual from the veindike magmas or at least are similar to these residues.

Certain veins in the Georgetown and Idaho Springs districts, in Colorado, afford data which illuminate the nature of the solutions which deposit the common type of massive sulphide veins. The veins are associated with the intrusion of Tertiary dikes into a pre-Cambrian complex. They are separable into: 1, argentiferous galena-blende veins; 2, auriferous and cupriferous pyritic ores. Most of the veins are plainly due to impregnation and replacement of crushed rock or fault gouge along the fissure zones which they follow; nevertheless, there are some striking and important cases where the same type of ores has filled fissures. The Terrible group of veins are mainly the latter type. The Mendota vein is characteristic of the group. These strong veins occupied open fissures, and were not formed by replacement: they contain numerous angular fragments of wall rock, and they are generally lined, between the rock walls and the massive blende which is the main vein filling, with a thin band of comb quartz. As to the origin of the fissures, the great length and even walls of some of the veins indicate a splitting open, with slight faulting.

I originally assumed that these sulphides were gradually deposited from thin aqueous solutions; but they show no banding, and I can now hardly avoid the conclusion that the veins were filled all at once, as if a solution "froze" into metallic sulphides.

The angular fragments of wall rock embedded in these sulphides

typically do not touch one another or the wall rock; therefore, I have rejected the theory of an original rubble-filled fissure, which I at first held. Close study of typical sections indicates that these fragments were held in suspension in the vein solutions which deposited the sulphides, in the same way that inclusions are held in rock magmas.

Do these fissure veins of the Terrible type belong to the group of veindikes? That the vein solution exerted some intrusive pressure is indicated by the spalling or splitting off by it of fragments and slabs of the wall rocks.

The Griffith vein, a few miles from the Mendota, shows two periods of fissuring and subsequent vein formation: first, a nearly pure sulphide vein of the Mendota type, inclosing angular fragments of the wall rock; and, second, after a renewed fissuring, a filling of pyrite and brown carbonates (of iron, manganese, and magnesium), with more or less quartz, and a very little galena, blende, chalcopyrite, and barite. There are angular inclusions of the ore of the first vein period in the later fissure filling; and these are frequently isolated and without support. I can conceive of no adequate explanation other than that the vein material of the second period was intruded in a viscous or gelatinous state, or in a condition between solution and crystallization; indeed, in nearly the same state in which I conceive the Mandy ores to have been intruded.

There is, occasionally, some evidence of a successive deposition in the carbonate stage; as, for example, a deposition, on galena fragments of the first vein stage, of first finely banded carbonate, next quartz, and finally the main carbonate-pyrite filling; but this does not conflict with the belief that the carbonate-pyrite solutions were highly concentrated, like those of the first vein stage.

The mixed carbonates of the Griffith vein represent a type or stage frequently found in ore deposits: therefore, the above observations may afford a clew as to the nature of certain vein-depositing solutions elsewhere (Chapter XVIII).

Pegmatites frequently show zonal or banded successive deposition of their constituent minerals; therefore, the proportion of water in the solutions which formed the Georgetown veins described is shown to have been not necessarily greater than in pegmatites.

The fact that ore deposition typically takes place at a certain sharply defined point in geologic time, just as dike intrusion does, is in accord with the conclusion as to highly concentrated ore solutions. Veins which prove this fact of having been formed at a certain sharp geologic point dispose at once of all uniformitarian theories of ore deposition. Such veins have not been formed by ordinary ground waters, whether descending, ascending, or laterally mov-

ing; and their contents have not been leached from rocks traversed by the solutions.

My own views as to ore deposition have gradually undergone evolution, since I believed in one instance (Monte Cristo) in the power of descending waters to form primary ore veins; and in another (Aspen) in the origin of the ores by hot-spring waters of ultimate surface origin; while for Georgetown I accepted the hypothesis of deposition by hot-spring waters which were magmatic emanations. We circle around truths, and, if patient, get ever nearer. I am now beginning to realize that in trying to identify vein-forming solutions with something we know, we are still not at the answer when we correlate them with hot springs.

At Tonopah, veins containing gold, silver sulphides, chalcopyrite, blende, quartz, adularia, and rhodochrosite have formed near the surface, in volcanic rocks, largely by replacement along fissure zones. Yet one of the largest, the MacNamara vein (mainly of quartz), is so situated that I must interpret it as intrusive, and as having lifted up in this act a load of overlying rock a thousand feet thick. Why is this more difficult to conceive than is the conception of an intrusive sill or sheet of igneous rock magma lifting the same load?

Therefore, I conclude that vein-forming solutions, whether at great depths, in the intermediate depths, or close to the surface, may in some cases be highly concentrated, and intrusive as veins or "vein-dikes." But vein solutions also frequently have the property of intimate penetration and replacement of rocks traversed; indicating in these cases much thinner solutions.

CHAPTER III

The Secret of Igneous Intrusion

I HAVE SPOKEN OF INTRUSIVE veins or veindikes; how are they intruded? How are dikes intruded? A dike half a mile wide cannot have filled a pre-existing fissure: we must grant an inherent dynamic intrusive potency. Early geologists were astonished at the conclusion involved in Gilbert's exposition of laccoliths, showing that a mass of liquid magma had lifted bodily a cover of several thousand feet of overlying strata. Gilbert did not grant inherent intrusive potency in the magma; he assumed intrusion to be a matter of relative specific gravity; but Cross showed that this was not true for the laccoliths. Existing theories of intrusion are still nebulous. Iddings, for example, states that the upward progress of magma, and its eruption, depends "on the dislocation and fracture of the lithosphere," without which there will be no intrusion. The liquid igneous

magmas, having nearly the same density as the solid rocks, and being under "hydrostatic pressure," may "permit fracture walls to separate, wherever the stresses within these walls tend to move them apart." My own imagination cannot follow this imaginative theory. Daly, on the other hand, has expounded a theory of intrusion, especially of great intrusive masses, as of granite, through the detaching by the magma, from the roof, of blocks which sink or are assimilated; and so the magma eats its way upward. This conception is plausible; but I have personally found little or no corroboration of it in the field. I see the same intrusion problem in narrow dikes and in great stocks or bosses, and there is every gradation between these.

In a locality in Saskatchewan, in the Archæan, there is gneissic gray granite, intrusive into greenstone schists; and this in turn is intruded by a red granite, without gneissic structure. A circumstance like this we usually explain by postulating a period of shearing between the two intrusions; but in this locality I found indications of a quite different explanation. The gneissic gray granite at one point is intruded by alaskite dikes of the second granitic period, and also by pegmatitic quartz veinlets of the same second period. There are also earlier pegmatite veindikes, belonging to the gray granite period, and these have partaken of the shearing.

In one instance noted, the effect of gneissic deformation was to fold a narrow pegmatite stringer, which runs at right angles to the gneissic structure, back on itself like an accordion, thus shortening its original length by a measured exact one-half. This shortening must have been accomplished by flowage. Whither did the lost volume of the now sheared granite flow? Various measurements on these veindikelets show a compression in two directions, at right angles to each other, on a horizontal surface; therefore, the direction of the gneissic flowage was *vertically up*. Measurements show a different total amount of flowage in different bands or zones. *Along the margins of the larger intrusive alaskite dikes the gneissic flow lines in the gneissic gray granite are strongly intensified, indicating that the flowage was connected with and was due to the dike intrusions.* This indicates that the shearing of the sheared gray granite was not antecedent to the intrusion of the unsheared red granite, but accompanied it, and was, in fact, caused by it. The process of intrusion and consequent shearing-flow of the intruded rocks was apparently leisurely. In some localities the intruded rock, although compressed along one horizontal axis, has been extended or pulled out along the other, but to an extent far less than the compression at right angles. Comparison of the ratio of compression and expansion in these cases, at right angles to one another and on the same horizontal surface, still indicates upward flow—at angles of 65° or so from the horizontal.

The area of this gray granite gneiss is very large; therefore, a great column of this granite has been propelled slowly toward the surface. Accordingly, the intrusion of the red granite was also very slow indeed. Such a slow regional upward movement must affect the surface of the earth and be expressed by a slow local or regional uplift or doming.

At Georgetown, in Colorado, there is also evidence that widespread schistosity in Archæan rocks may have been due to flowage under the intrusive pressure of later granitic magma masses; and that with the end of intrusion there has been an end of shearing. Imagine, in the Georgetown case, the adjustments of the older rocks being pressed back by a body of intrusive magma ten square miles in horizontal section. At the great depths at which the intrusion took place the adjustments must have been made by flow; and this flow, producing the observed schistosity, will have affected the intruded rocks far up beyond the actual position of the intruded magma at any given period.

Therefore, my interpretation of intrusion is that the intrusive fluid is under pressure strong enough to thrust up and aside miles of rock; and that this power resides in the magma which forms a narrow dike just as it does in a great mass. Is this intrusive pressure a transmitted pressure, derived originally from movements in the solid crust and unrelated in origin to intrusion; or is it an inherent expansive force? I accept the second alternative. The expansive forces of compressed gases in magmas must be very great.

Since the ascent of great igneous masses must in some cases amount to many thousands of feet, the uplift at the surface would have the corresponding titanic dimensions; and the upward intrusion of dome-shaped igneous masses would produce domical uplifts at the surface. Geologists are familiar with such uplifts, of all dimensions: and it seems unavoidable that at least some of these must have had this origin. The slowness of such surface uplifts testifies to the leisurely upward intrusion at depth. Therefore, some intrusions must be vastly slow; whereas some, as we know in the case of surface lavas, must be very sudden.

Dome-shaped intrusions, or batholiths, are most characteristically found in the deepest-seated rocks, which have been most deeply eroded; and every evidence is that these bosses occupy broader and broader areas with increasing depth.

If the inherent or telluric pressure of liquid magmas is due to compressed gases, then it would perhaps be more powerful in the siliceous magmas, which are supposed to contain a large portion of volatile constituents. At any rate, the telluric pressure of pegmatite

and quartz magmas is shown, by their intrusive phenomena, to be tremendous.

Evidently the fluid condition of all magmas is maintained by a combination of pressure and temperature.

CHAPTER IV

Igneous Surgence on Local, Regional, and Continental Scale

SUBSEQUENT TO GILBERT'S discovery of laccolithic intrusion, doming up the overlying intruded strata, Russell called attention to cases of intrusive rock in the form of pipes or plugs which never reached the surface. In 1898, I described the geology at Aspen, Colorado. The district shows alternate uplifts and subsidences, from the pre-Cambrian to the Cretaceous, without evidences of volcanic activity; but the final great uplift, at the close of the Cretaceous, was accompanied by the intrusion of great masses of magma, as if the uplifting were accompanied by the subcrustal accumulation of molten rock. If this is the case for the final great post-Cretaceous uplift, is it not a fair assumption that the earlier recurrent mighty elevations were also in some way connected with magma accumulation, albeit none of the magma reached the superficial portion of the crust?

At Aspen, profound folding and faulting followed directly upon these intrusions, and, therefore, probably has a genetic connection with them; and I believe that the dynamic disturbances were a *consequence* of the magma migration. Near Aspen, the whole Sawatch range was uplifted; and in the Aspen district itself there was a very local doming-up, accomplished mainly by complex faulting, of an area more than a mile in diameter, which was uplifted about 5,000 feet. The phenomena indicate a slowly rising magma plug beneath. If this is the case, the broader contemporaneous doming of the Sawatch range may also have been due to post-Cretaceous magma uplift or surgence at its roots. Where the pre-Cambrian rocks are locally exposed in this range, there outcrops a boss or dome of granite, intrusive into older gneiss. Ore deposits (pre-Cambrian) are associated with this intrusive rock, as ore deposits are with the post-Cretaceous intrusions. There were no other periods of intrusion, and none other of ore deposition, in this range.

The Mosquito range, near the Sawatch, has been uplifted along a series of large faults, which followed a period of copious igneous intrusion. What was the slow, local uplifting force? An uprising body of magma at the roots of the range is suggested.

In the San Juan region, in Colorado, the San Juan Mountains form a broad dome-shaped, post-Cretaceous uplift. Several lesser domal

uplifts have been superimposed on the main dome structure. The San Juan region is one of great igneous activity, and the igneous rocks are closely related chemically to one another, and also to porphyry masses in other parts of Colorado and adjacent parts of Utah, Arizona, New Mexico, and Mexico. An underlying magma basin of considerable importance is therefore indicated; and the domes, both the large and the local ones, are apparently due to upward protuberances of this underlying magma. In Colorado, intrusions of rock belonging to the Early Tertiary monzonitic magma form an isosceles triangle some 200 miles on a side; this triangle comprises a large part of the main Rocky Mountain uplift of Colorado, which was post-Cretaceous, and which is assumed to have been due to the same force which uplifted the smaller domes.

Passing southward in this general petrographic (and metallographic) province, to Mexico: in the State of San Luis Potosi, at Matehuala, an intrusion of monzonite much less than a mile in diameter is surrounded by limestone strata dipping away to form a dome, bounded on one side by a fault. But the faulting and doming was subsequent to the intrusion and to the ore deposition which followed the intrusion. Accordingly, it is believed to have been due to the upward pressure of the unconsolidated portion of the igneous plug in depth; and there is some reason to believe that the uplift kept pace more or less with the stripping off of the updoming rocks by erosion, indicating that the dome was and is in a state of rather delicate balance.

One hundred and fifty miles north of Matehuala, near Monterey, there are many dome uplifts in limestone which show no igneous rocks, but do show ore deposits. I have no doubt that they are due to the upward pressure of igneous magma fingers below. Some 200 miles west of Monterey, near Velardeña, the San Lorenzo range has been recently uplifted, as an elongated dome; and evidence warrants the assumption that the uplift is due to the upward movement of unconsolidated magma below. Fifty miles north of Velardeña, at Mapimi, a bold domical mountain of limestone shows, in addition to the general domical structure, close overthrown folding in one belt, and even some overthrust faulting, which folding and faulting are indicated as due to different pressures or thrusts, coming from different directions. Local forces are indicated, and these can only have been due to the intrusion of igneous masses; and the intrusive shove which formed the main dome is shown to have moved upward diagonally, at an angle of 65 to 70° from the horizontal.

Both intrusive diorite and alaskite occur in the range. The alaskite does not outcrop, but is found in drill holes 3,400 feet below the mountain's base. The diorite intrusion was later than the doming; nevertheless, it is a permissible hypothesis that the exposed intrusive

diorite masses were later emissaries of the buried diorite magma column, and that an earlier upward movement of the column caused the doming. Plainly, the doming impulse may come from slow upward intrusion at considerable or great depths. The domical type of structure, then, and not the presence of intrusive rocks, is the criterion. On the flank and at the base of the main Sierra de Mapimi dome is a local dome of later origin than the main dome, and contemporaneous with the diorite intrusion.

These investigations of the Sierra de Mapimi explain the origin of the irregularly shaped and distributed, often dome-like mountains of this section of Mexico, as due to the force of intrusión of domes or fingers or belts of magma slowly moving upward during a vast period of time—during the whole Tertiary, and down to the present. Moreover, the interpretation of the Sierra de Mapimi shows that close and even overthrown folds, and even overthrust faults, may be due to the horizontal element in upward igneous intrusions. May this sometimes be the cause of overthrown folding on a larger scale?

In all these Mexican examples intrusion was not "permitted"; it was due to the gigantic telluric force residing in the magma, a telluric uplifting force, which is, however, often in equilibrium with the gravity pressure of the overlying rocks.

We have studied, in this Mexican field, the uplifting force of separate small intrusions; but the hollows between these local uplifts are not crustal depressions—the whole region has been uplifted. This broad uplift is the Mexican Plateau, which connects with other plateaus as far as Colorado and Utah, and further, so that this uplifted area comprises a large part of North America, from the Rockies west. The Colorado Plateau and the so-called Great Basin of Nevada are parts of this great uplifted continental segment. The slope of the Great Basin Plateau toward the Sierra Nevada may represent the western slope of the great flat arch of uplift, and the slope of the Great Plains from the Rocky Mountains to the Mississippi, the eastern slope. Many indications show that this great continental swelling has continued till quite recently, or is still in progress.

Like the Mexican Plateau section, the Nevada-Arizona region has undergone repeated folding, faulting, and intrusion from the Jurassic to the present. Most of the ranges are not recent, and their relief has been mainly determined by differential erosion; this applies especially to the larger part of Nevada. But there is a relatively narrow belt immediately east of the Sierra Nevada, where the mountains and valleys are of mainly later origin, and have been formed principally by direct crustal deformation. Such is the origin of Death Valley, and many other valleys and ranges. Both flexing and faulting effected the observed deformation.

The east face of the Sierra Nevada is along a great fault. Many of the ranges in the belt east of the Sierra Nevada are domal uplifts, whose origin I assume to be, like the Sierra de Mapimi, in Mexico, due to the upward pressure of magma columns at their bases. On the whole, this belt east of the Sierra Nevada is a relatively depressed one, as compared with the belts east and west of it; and this relative depression or trough is of long standing. In the Sierra Nevada great intrusions of granodiorite took place at the close of the Jurassic and probably accomplished the elevation of the range, and I assume that the force of this intrusion accomplished the folding and schistosity of the intruded strata. There is some overturned folding, overthrown to the west in the belt west of the main granodiorite intrusion, and to the east in the belt east of this intrusive axis, indicating lateral thrust from the intrusion against the rocks both east and west.

The relatively depressed belt of valleys (between important mountain ranges) lying east of the Sierra Nevada has been maintained since the uplift of the Sierra in the late Jurassic. The belt has been the site of land-locked lakes ever since. The continual changes of position and area of these lakes show active warping of the crust throughout the Tertiary, with important elevations and depressions.

The Sierra Nevada range itself has been repeatedly uplifted, along the fault which is its eastern boundary; and this faulting extends to the present day. The range, though continually reduced by erosion, has had a recurrent spasmodic growth. Thus a persistent fault block, of continental-unit dimensions, has been repeatedly pushed up by some force at its base, acting in large measure vertically from below. This force can be none other than the pressure of the body of magma at its base, which has sent up offshoots, from the close of the Cretaceous to the present.

The small typical uplift of the Sierra del Fraile, at Matehuala, along a fault at its base, enables us to understand the force which uplifts the Sierra Nevada. Also, as a sidelight on the recurrent and spasmodic periods of movement along the Sierra Nevada fault zone, we may consider a smaller example I worked out at Ray, Arizona. At Ray, pre-Cambrian schists are overlain by Paleozoic stratified rocks. Near the close of the Cretaceous, a great dome of granite worked upward into the schists, and ore deposition followed. Directly after the ore deposition, a great vertical fault—the Ray fault—cut through the mineralized district in a north-south direction, and uplifted the country on the west side one or two thousand feet. Erosion leveled the uplifted block to the same level as the other; then, at the end of the Tertiary, the same west-side block was again uplifted a thousand feet; and again erosion reduced all to a level. Later there

was a general uplift, and the block on the west side was relatively dropped a few hundred feet. We must ascribe the uplifting of at least three thousand feet, in two distinct and separate waves, to the upward pressure of the igneous magma below. This indicates periods of accumulated pressure, which became strong enough to overcome the weight of overlying rocks. If this explanation of recurrent uplifts is true at Ray and for the Sierra Nevada, may it not be true of the Rocky Mountain uplift, and indeed of the whole Cordilleran region, which has experienced recurrent uplifts? May it not be true of the recurrent uplifts of the continent as a whole? The main monzonite magma which has repeatedly uplifted the Sierra Nevada is essentially the same as the average magma of the Rocky Mountain belt, from Mexico to Canada. There seems little doubt that one magma basin underlay at the close of the Cretaceous this whole western part of North America, and still so underlies, at least in the western part. Moreover, over large portions of this basin, at least, the same processes of differentiation in this primary magma have gone on at much the same time. In 1900, I divided the complete differentiation cycles in Nevada into two, each signalized by the development of the complementary siliceous and basic lavas—rhyolites and basalts—from intermediate types—andesite; and between the two cycles I postulated a grand intrusion revolution, consisting in the arrival, in the magma basin below, of a fresh supply of undifferentiated intermediate magma. Ball later corroborated these conclusions. I now believe there may have been three instead of two of these differentiation cycles.

The deduced recurrent fresh supplies of the undifferentiated intermediate magma recall the described recurrent main periods of uplift of the Sierra Nevada, which appear to be of about the same order of frequency. Therefore, the Sierra Nevada recurrent main periods of uplift may have been due to these periods of arrival, at its base, of fresh supplies of intermediate magma, which was thus elevated into the zone of differentiation. Once transferred to the zone of differentiation, the magma seems capable of differentiation within a comparatively brief geologic period, as shown by the Great Basin cycles, all three of which occur within the Tertiary period.

Where did these recurrent fresh magma supplies come from? There is evidence that a single general type of Tertiary magma eruptions rims the whole Pacific, on both the American and the Asiatic sides; and therefore it is probable that one basin of intermediate magma underlies the Pacific basin; that this flows slowly laterally toward and beneath the continents, and enables them to retain, by repeated uplifts, their relatively elevated position, in spite of constant erosion. The differ-

ences in density between continents and ocean basins which induce this flow, are, for all we know, original. The difference has been established by gravity measurements; and also the rough constant relation of density to earth radius or surface relief, which is called "isostasy."

Geologic history shows that the adjustment by flowage to compensate erosion is not free, but that unbalancing by erosion, and the consequent accumulation of strains, goes on for a long period; then sets in a correspondingly marked period of uplift and perhaps of surface volcanism, which by its momentum may pass the point of equilibrium.

The creep of the subcrustal magma from the ocean produces a thrust toward the continents, and a consequent folding and faulting on their margins. Therefore, in the broadest sense, I refer practically all crustal movements to magma migration.

After surface volcanism, the loss of gases produces a decrease in volume which often results in a sagging of the volcanic area, as shown at Tonopah by the subsidence of volcanic necks. This subsidence is here widespread, so as to suggest that it may well account for the great depressions filled by the successive Tertiary lakes of this region.

In certain parts of that relatively depressed belt which lies east of the Sierra Nevada—the Sierra Nevada back-trough belt—there is locally a notable great difference of elevation between ridges and contiguous basins. Between the Walker River range and the valley basin at its foot, for example, there is a difference of about 7,000 feet, and the highest point of the range lies opposite and close to the deepest portion of the basin. Both range and basin appear to be due to relatively recent crustal deformation. This "pairing" of mountain and basin, of greatest elevation and greatest depression, suggests a certain connection or compensation between ridge and valley. Similarly, and in the same belt, the highest and the lowest points in the United States (Mount Whitney and Death Valley) are only eighty miles apart, with a difference of elevation of nearly 15,000 feet. Other examples suggest the same principle of pairing or compensation.

I look with favor on the explanation that the weight of very recent uplifts may be so great as to cause them to sink slowly, carrying down as parallel depressions the adjacent strips; and accordingly, on a grander scale, that the whole Sierra Nevada back-trough is due to the sagging of the Sierras. And this leads to a consideration of a still larger geologic feature—the deep narrow troughs—"foredeeps" of Suess—in the Pacific, rimming the continents, or on the margin of the submerged continental shelf. I note "pairing" in this instance also; as in Chile, where the difference in elevation of the mountain

tops and the bottom of the parallel foredeeps reaches between 40,000 and 50,000 feet. I believe the foundation of the Andes has sagged and dragged down this marginal trough.

Other instances of foredeeps around the Pacific can be explained only by a corresponding swift sagging of the continental mass, including the continental shelf, as a whole. These marginal troughs must have been formed with great rapidity, geologically speaking; the transportation of detritus from the land by erosion will normally soon fill and mask them.

Therefore, the earth's crust, in many regions at least, is not in equilibrium, as postulated by the theory of isostasy, but is in a condition of unstable equilibrium, which seeks adjustment, but is unable to attain it, because of the idiosyncratic behavior of the subcrustal magma migrations.

What connection has all this with ore deposits? This common and universal Pacific magmatic or petrographic province shows, also, all around the Pacific, a belt of enormous and roughly similar later Tertiary mineralization; so that, in this case, also, volcanism and ore deposition were allied phenomena. The Nevada type of Tertiary ores is traceable around the Pacific.

CHAPTER V

The Sequence of Ore Magmas

IN CHAPTERS I and II, I pointed out that there originated, as later products of differentiation from magmas, pegmatites, locally metalliferous, containing, for example, molybdenum; that as more highly differentiated products, gold-quartz veins arose; as still more advanced stages, arsenopyrite, pyrite, or chalcopyrite; and that a still further advanced stage was zinc blende. I showed that many of these mineral veins were injected as highly concentrated solutions or almost pasty fluids. In Chapter III, I tried to show that the cause of intrusion or injection was an inherent telluric pressure; and to this I traced (Chapter IV) not only dike and vein injection, but domal uplifts, the uplifts of ranges, and the maintenance of continents. In Chapter V, the sequence of the different metals as magmatic stages will be further considered.

In the deep-seated gold-quartz veins the metallic sulphides tend to be deposited later than the quartz. Veins of this type—the California type for example—are injected or intrusive; their vertical range of deposition is indicated at several miles. The chalcopyrite, arsenopyrite,

or pyrite, which forms the zone normally next vertically above, also frequently shows evidence of origin by injection.

The vein sequence at Matehuala, in Mexico, is most illuminatingly shown. First came barren lime silicates; then cupriferous pyrite; then arsenopyrite; then pyrite and pyrrhotite; then zinc blende; then galena; and finally barren calcite. The solutions from which all these were deposited are believed to have been extreme siliceous magmatic residues from a monzonite magma.

The superimposed sequence resulted from a falling temperature, which caused the vertical downward migration of characteristic metal zones. At the end of the sequence, vein formation was at an end, for all time. There is in this district an immense post-mineral fault, which throws down the zone of commercially important auriferous and argentiferous arsenical pyrite veins on one side of the fault to the level of commercially important copper pyrite veins on the other side. The copper deposition may have taken place somewhat below 550° C.; and the copper-arsenic vertical range of deposition was at least a mile, and probably much more.

At Mapimi, in Mexico, there is a gradual transition from the galena-blende zone above, to the copper-bearing zone with lime silicates in depth; the vertical extent of the galena zone is about 3,000 feet.

At Velardeña, in Mexico, we have the sequence: copper, arsenopyrite, zinc, lead, silver. The ores are genetically connected with a differentiated dioritic intrusive magma. Lime silicates were formed subsequent to the intrusions; and their formation was independent of the varied rocks which they replaced, as at Matehuala. The most basic of the three principal intrusive areas is cut by regular parallel ore veins. The principal vein shows the deposition sequence: 1, cupriferous pyrite; 2, galena and blende; 3, argentiferous and auriferous tetrahedrite. Barren calcite veins are the latest phase. The most siliceous of the three intrusions is accompanied by marginal ore pipes, at the contact of intrusive rock and limestone. The ores are more highly cupriferous than in the veins above mentioned: they are of the type which have been called "contact metamorphic," but they and the fissure veins above mentioned are clearly both variations of a single group.

The parallelism of sequences in different districts like Matehuala and Velardeña is so minute and orderly as to indicate a fixed law.

At the Angangueo mines, in Mexico, fissure veins in Tertiary andesites show the sequence: 1, pyrite and cupriferous pyrite; 2, blende; 3, galena (argentiferous); 4, quartz (argentiferous); 5, manganese carbonate.

In the district of Tepezala and Asientos, in Mexico, are rhyolitic

necks intrusive into Mesozoic thin-bedded limestone. Three adjacent necks are found to be each of different age. There is associated ore deposition, which appears to be nearly contemporaneous with the intrusive of the middle period. The earliest neck, together with the adjacent intruded sedimentary rocks, has been rendered schistose by subsequent local flowage; I ascribe this to the pressure of the upwelling igneous column below. The schistose rhyolitic neck has later been uplifted bodily by this force, as a block between two parallel normal faults. The period of uplift was the period of intrusion of the neighboring rhyolite neck of the middle period. The fault fissures mentioned are filled with copper pyrites, with lime-silicate gangue, as well as quartz and calcite. The same temperature-pressure stage of copper deposition as at Matehuala and Velardeña is shown; at the latter places they are of the type usually referred to as "contact metamorphic." Nevertheless, at Matehuala at least, these deposits have been controlled by fissures, especially at the contact; but at Tepezala the ore has been infilled into open fissures, 15 to 25 feet wide. These fissures could not have remained open if empty; the telluric pressure of the vein-forming solutions must have held the walls apart while the solutions leisurely crystallized. The filling is independent of the wall rock. About a mile away from this volcanic center are veins of chiefly galena and blende, with a mainly quartz-calcite gangue; and still further away is the Santa Francisca vein, at Asientos, a silver-bearing quartz vein (with considerable galena and blende). This vein is as much as 40 to 50 feet wide, and is banded. We have accordingly in this district, in the center of the district, copper-bearing veins; on the flanks, lead-silver veins; and on the margin a principally silver-bearing vein. These stages apparently depended on relative temperature.

These examples illustrate the law of metal sequences which I outlined in 1912: A, tin, molybdenum, tungsten, etc.; B, gold; C, copper; D, auriferous and argentiferous pyrite and arsenopyrite; E, zinc; F, lead; G, silver. Originally, I included certain gold ores under G, but I will discuss this later as an uppermost zone. Zones A and B are associated with coarsely crystalline igneous rocks; C and D with finer holocrystalline or coarse porphyritic intrusives; E and F, typically with fine-textured porphyries, or immediately adjacent igneous rocks are lacking.

A reversal of sequence is obtained by deposition during a rising temperature, due to slow upward igneous migration in depth. Thus, at Aspen we have the sequence: 1, barite; 2, rich silver ores (Zone G); 3, lead and zinc (Zones F and E). The Tiro General vein, in Mexico, similarly shows: 1, zinc (Zone E); 2, copper (Zone C).

CHAPTER VI

The Near-Surface Telescoped Ore Deposits

I DISCUSSED in Chapter V the sequence of metallic deposits, from the normally deep-seated tin and tungsten zone to the principal silver zone, normally far above. This principal silver zone was in many cases still formed at no very shallow depth; in certain camps in Colorado, for example, it seems to have formed below 3,000 feet. But it is well recognized that abundant ore deposits take place at lesser depths, in the upper 3,000 feet and even 1,000 feet of the earth's crust. These shallow-formed ore deposits are mainly associated with Tertiary surface volcanics. They have a relatively limited vertical extent, as compared with ores formed at greater depths; they are usually complex in nature, but are remarkable for their high content in silver and gold. Nevertheless, in many cases they contain notable quantities of the "base" metals, such as copper, lead, and zinc; or even tungsten. Tin also occurs occasionally in these surface volcanic rocks. Thus, on the basis of conclusions set forth in preceding chapters we should conclude that these represent the whole temperature range of ore deposition, from tin and tungsten to silver; and that the temperature of these surface lavas was as great as or greater than that of the rocks inclosing the whole metallic vein sequence, in depth.

Where a magma reaches the surface, it apparently arrives there with no loss of heat; and the cooling is so sudden that, when ore magmas penetrate these rocks, the ores of the different vein zones are deposited in nearly the same vertical range, one on the other in quick succession; and are so effectively superimposed that they mingle and may be termed "telescoped." Fumarolic deposits in fissures in volcanoes actually show the whole range of metals, from tin to lead.

At Tonopah there were formed, in quick and irregular succession, tungsten, copper, zinc, lead, silver, and gold ores. The gold probably partly represents a superficial zone, not recognized (since not present) in studies of deeper-seated veins. If this is true, important gold ores are recurrent, at three separate stages in the ore column; silver also occurs at two separate stages; but tin, tungsten, copper, zinc, and lead occur each at a single major stage only. Adularia is characteristic of the Tonopah ores and others of the Tertiary shallow-formed type; it has been sometimes regarded as a low-temperature mineral; but it is frequently characteristic of fairly high-temperature conditions.

Certainly the deposits of metallic minerals around the fumaroles of

volcanoes are not "low-temperature" deposits. These are not found on all volcanoes.

Between the deep-seated group of ore deposits, showing more orderly and vertically extended zones, and the telescoped superficial deposits formed at the same temperatures, comes an intermediate group connected with intrusive rocks of the middle depths. The maximum vertical zone of deposition at the plutonic depths can hardly be less than five miles; but in the near-surface deposits all the zones are deposited within a maximum vertical distance of a few thousand feet. The deposits of the intermediate depths have, of course, intermediate characteristics. Complex practically contemporaneous ores result, in the shallow-formed group; in the intermediate group, more typically composite (compound) veins, formed by the overlapping or superposition of one zone upon another.

CHAPTER VII

The Aplitic, Pegmatitic, and Superpegmatitic Rock and Ore Magmas

ALASKITES (quartz-feldspar igneous rocks) are fine, intermediate, and coarse grained—of aplitic, granitic, or pegmatitic texture. At Helvetia, in Arizona, the sequence of intrusions was: 1, biotite granite; 1_a, pegmatites and pegmatitic quartz; 2, alaskite-granite porphyry; 2_a, diorite and quartz-monzonite dikes; 3, alaskite aplite; 3_a, pegmatite and pegmatitic quartz; 4, quartz aplite or arizonite; 4_a, metalliferous quartz veins. Arizonite is an alaskite with the feldspar so subordinate that quartz is by far the most important constituent.

The general process illustrated by 1, 2, 3, and 4 is a growing siliceousness in the magma. The aplitic texture of the arizonite shows that this residual quartz magma was not attenuated and aqueous. The alaskite aplite was followed by coarse pegmatites and also by the more abundant aplitic arizonite. This squarely defines the practically contemporaneous existence of two siliceous magmas of similar composition, the one highly fluid and attenuated, the other viscous and poor in mobile constituents.

What is true of the alaskite magma—the separation by differentiation into a relatively dry and a relatively aqueous magma—an aplitic and a pegmatitic magma—is probably true also of ore magmas. At Santa Eulalia, in Mexico, are ores in Mesozoic limestone, of two types. The prevalent type is blende-galena-silver ore, containing some pyrrhotite. The second type consists of pyrite and pyrrhotite, carries considerable silica and a little gold, and has the ferrous silicate fayalite as an abundant gangue mineral; also, ilvaite (iron-lime silicate) and knebelite

(iron, manganese, and magnesium silicate). Fayalite was here for the first time recognized as a gangue mineral with ores; it has been reported almost exclusively from igneous rocks. The galena-blende ores are later than the argentiferous pyrite ores; but the two types have certain minerals, like pyrrhotite, in common. The association of gangue minerals indicates that the argentiferous pyrite ores here at Santa Eulalia were deposited at a higher temperature than the corresponding ores at Matehuala, which is also in Mexico. There are no associated igneous rocks, but the data indicate a large body of magma below, at the time of ore deposition. The argentiferous pyrite ore, with largely silicate gangue, occurs as a regular fissure vein in limestone: but the limestone in the walls is not altered to silicates. Moreover, the silicates of the gangue are phenomenally poor in lime, although the magma solution has traversed thousands of feet of limestone. The deduction is that the ore was intrusive in a fluid but highly concentrated state, containing no more water than do basic igneous dikes. The ore magma was also short of sulphur as compared with iron. The Potosi veindike is in this sense an aplitic type, the result of crystallization of a relatively dry and viscous ore magma. The corresponding pegmatitic ore magma—i. e., containing more water—would have formed replacement deposits in the limestone, as do the later galena-blende ores; and, indeed, the argentiferous pyrite ore at Matehuala was by contrast somewhat aqueous, since it replaced limestone.

I am inclined to add a third division of magmas, based upon the relative content of water and other gases—to add to the aplitic and pegmatitic divisions the superpegmatitic division, in which the gaseous elements become predominant.

At Velardeña, we have, it will be remembered, several magmatically related intrusions, variations of a dioritic or monzonitic rock, which have produced, in the different intrusions, diabase, diorite, and monzonite respectively. Field and microscopic studies show a sequence of crystallization, similar in all three stages; and also that the rock minerals grade into the crystallization of pegmatites and these into veins. The whole sequence is: 1, andesine-oligoclase and some hornblende; 2, magnetite, biotite, and grass-green pyroxene; 3, orthoclase, apatite, titanite, chlorite, quartz, pale-green pyroxene, pyrite, chlorite, fluorite, zircon; 4, garnet and pale-green to colorless pyroxene; 5, cupriferous pyrite, pyrite, quartz, and calcite; 6, blende and galena; 7, tetrahedrite, quartz, and mixed carbonates; 8, quartz and mixed carbonates; 9, calcite. Each of these stages may replace earlier stages. Stages Nos. 2 and 3 especially replace stage No. 1, and I infer a superpegmatitic rock magma representing these 2 and 3 stages.

The term "contact-metamorphic" ore deposits is in most cases a

misnomer: they are often neither metamorphic nor essentially contact deposits, but are replacement or metasomatic deposits at an elevated temperature.

At Helvetia, also, an intrusion of granite shows the following sequence of crystallization: 1, oligoclase-andesine feldspar, and pyroxene or hornblende, forming a dioritic rock; 2, orthoclase, quartz, muscovite, biotite, chlorite, zircon, apatite, and magnetite. Stage 2 has replaced stage 1. Thus the original diorite has been invaded and replaced by superpegmatitic granitic magma.

CHAPTER VIII

The Time Relation Between Rock Intrusion and Ore Intrusion

SO FAR AS I HAVE SEEN, all igneous rocks are intrusive in the broad sense: that is, they are all migratory rocks that have ascended from a deeper source. The more deep-seated and larger bodies must, however, have been impelled by a less degree of inherent telluric pressure than those magmas which reach the surface. The gaseous pressure which probably constitutes this telluric force will tend to accumulate in the upper portions of upreaching magma fingers or in the summits or cupolas of magma domes; and since the gaseous elements are also closely connected with certain phases of ore deposition, the latter may also take place preferentially at the top or even above the top of such a magma body.

Magmatic ore deposits, including mineral veins, usually depend for their localization upon fissures in the solid rock, in which they form. These fissures not only govern the position of veins and veindikes, but of dikes also; and frequently the same fissure-plane is successively penetrated by a dike and a vein. The rule, which is subject to exceptions, is that the dike comes first. In the same way, in a regional sense, igneous intrusion characteristically precedes ore deposition; and the evidence is that the former *immediately* precedes the latter. After the igneous intrusion, the ores form along fissures; and these are generally fissures of slight fault displacement, though again there are exceptions to this rule.

Subsequent to a brief period of ore deposition, rock movement and faulting goes on for very long periods, often lasting to the present day. What is the cause of this enormously protracted fault movement? In at least one type of occurrence, at Tonopah, the faulting was caused mainly by the unequal settling back of the volcanic rock after intrusion, producing complex differential movement; though some faulting accompanied the intrusion. The major slow adjustment following intrusion resulted in a differential sinking, affecting wide areas.

Therefore, instead of the two closely allied phenomena, volcanic intrusion and folding and faulting, both being due to an unknown cause, I recognized that the latter may have been due to the former, as a general fact as well as in the Tonopah instance.

The general rule that ore deposition takes place in a very brief period immediately subsequent to igneous intrusion proves that metalliferous veins are a phase of igneous activity. If we accept the rule, we may deduce the magmatic nature of orebodies where the above sequence of events is found, as is the case with the lead-zinc deposits of Missouri and the copper deposits of Michigan.

Examples of this rule of sequence (stated above) are afforded by the mining districts of Matehuala and Velardeña, in Mexico, and Georgetown and even Leadville, in Colorado. Aspen, in Colorado, shows a variation from the rule; for the ores formed along fault fissures only after considerable faulting had taken place—more than at Leadville, where the amount of faulting (100 feet in one case) preceding ore deposition is already in excess of the rule. One of the typical Aspen faults shows a displacement of 750 feet, of which 350 was pre-mineral and 400 post-mineral. The ore deposition consisted of three successive stages; and the entire ore deposition took place along the growing fault in so short a space of time that only a barely perceptible faulting occurred in the meantime.

A consideration of these relations indicates that while faulting has been in progress for millions of years, the period of all ore deposition requires at most the assignment of tens of thousands, a period very similar to that which we may assign to the analogous phenomenon, dike injection. But in making this comparison, we must realize that in different cases the time occupied by the act of igneous intrusion varies exceedingly, from the unusually slow upward surgence of plutonic igneous masses to the very rapid injection of dikes at the surface.

Where faulting has made considerable progress before ore deposition, it probably means that the earlier fissures had failed to tap an ore-magma basin or pocket; where an igneous intrusion is not followed by any mineralization, it may mean that the fissures have not tapped any ore-magma basin, or it may mean that no ore magma was developed. Ore-magma basins or pockets are apt to be at the summits of domes or other igneous masses, on account of the buoyancy (due to high igneous or telluric pressure) of the ore magmas.

In such natural traps or pockets material of diverse origin may gather and mix, as helium and natural gas, the former of probable magmatic origin, the latter of organic and more superficial derivation.

The ore magmas are believed to develop only under plutonic conditions, and, therefore, are most likely to follow immediately intrusion in the case of plutonic intrusions. Hence, ore deposits connected with

deep intrusive rocks should show fewer variations from the rule that they occupy fissures of slight displacement than those connected with volcanic rocks; also, the plutonic or most deep-seated types of veins should show most approximation toward the rule.

An extreme case of a wide time interval between intrusion and ore deposition is that at Tepezala, where the intruded rock had been rendered schistose in the interval. There is here evidence, however, that the ore is not genetically connected with the schistose igneous intrusion on whose contacts it has been deposited, along fault fissures, but with a subsequent igneous intrusion. This suggests the rule that metalliferous veins are not intimately connected genetically with igneous intrusions, from which they are separated by a considerable time interval. Tiro General, in Mexico, furnishes another example of this truth. These are "false" contact deposits.

With greater and greater depth, does the period of igneous intrusion and consolidation and that of ore deposition draw closer together, and are both contemporaneous in some cases? I have been unable to find such an example in the copper deposits; and this confirms my conclusion that the ore magma is not the residual fluid expelled from igneous rocks during forced crystallization, but is a special magma developed at the deep zone where rock differentiation takes place. This means that volcanic emanations do not represent ore magmas, even though the former bring about scanty metalliferous deposits, of scientific interest only.

The copper deposits associated with lime silicates on igneous contacts are, in my experience, always of later origin than the intrusion of the igneous rock; therefore, for their source we must took lower, thousands of feet deeper, down to the differentiation zone, which is laid bare to us by erosion in the case of some metalliferous pegmatites. The ore magmas must take an immense time to form; and the pegmatitic ore magma may split into dry or aplitic phases and highly aqueous or pegmatitic phases. Mineral deposits formed from volcanic emanations, such as borax, soda, and alum, are not formed from the ore magmas proper.

CHAPTER IX

Epochs of Ore Deposition

IT HAS COME to be pretty widely recognized that ore deposits are characteristic of certain brief geologic epochs only, and that between such epochs, for many millions of years, there has been no ore deposition. This fact of and by itself disposes of uniformitarian theories of ore deposition for the ore deposits in question. It has

also been well established in recent years that the critical periods of ore deposition were also periods of igneous intrusion; and, also, of the folding and faulting of rocks. All these three groups of phenomena, therefore, are catastrophic rather than uniformitarian in nature.

There were epochs of ore deposition in the pre-Cambrian, but the pre-Cambrian is not an open book for us. In the post-Cambrian, the Appalachian belt was during the Paleozoic the site of folding, intrusion, and ore deposition. During this period, the region from the Appalachians nearly to the Pacific Coast was comparatively quiet and undisturbed.

The history of the Rocky Mountains, as exhibited at Aspen, is typical of the geologic history of a large part of the western region of the United States. Colorado, speaking broadly, was a granite-gneiss island in the pre-Cambrian ocean. Repeated up-and-down oscillations took place during the Paleozoic, resulting in a Cambrian sandstone deposit, a Silurian limestone, a thin shaly Devonian formation, and an early Carboniferous limestone. After a great uplift, without folding, there formed, in the Permian period, thick sandstones and limestones; and rapid sandy sedimentation also characterized the Triassic-Jurassic. In the early Cretaceous period thick shales and limestones were deposited. Finally, at the end of the Cretaceous, came the first great catastrophic epoch or series of epochs which had occurred since the pre-Cambrian: for the intrusion of igneous rock and ore deposition took place for the first time. These events recurred during the Tertiary, from time to time.

In the present Pacific Coast region, however, there were catastrophic periods, with volcanic outbursts, as far back as the early Paleozoic, and an important period of intrusion, folding, and ore deposition in the Permian-Triassic, and again at the close of the Jurassic. This last catastrophic epoch was manifested as far east as central Nevada. But when at the close of the Cretaceous the invasion of igneous rocks finally took place in Utah and Colorado, it did not take place in Western Nevada and further west; though the Tertiary volcanics characterize the whole belt from the Pacific to the Rockies. We are still living in the Tertiary catastrophic period.

Summarizing, during the Paleozoic both the present Pacific Coast and the present Atlantic Coast were established as magma provinces, with igneous intrusion, folding and faulting, and ore deposition. Igneous activity and ore deposition took place in the Pacific Coast region in the Permian-Triassic; and at the close of the Triassic, along the Atlantic border, basaltic intrusion and some ore deposition took place. On the Pacific Coast a period of major revolution occurred about the close of the Jurassic and the beginning of the Cretaceous.

Still later, at the close of the Cretaceous, came the establishment of the great magma province in Utah and Colorado.

Between the Appalachian belt and the Cordilleran belt of catastrophic magma activity there lies the contrasted Mississippi Valley province, where the strata have remained nearly horizontal since before the Cambrian. But west of the Appalachians, running from New York to Missouri, there is a chain of faults, anticlines, and very basic dikes (peridotites) of probably post-Cretaceous age—corresponding, therefore, to the Rocky Mountain post-Cretaceous catastrophic magma period. Along this chain, and often closely associated with the dikes, are abundant deposits of barite, fluorite, lead, and zinc, with a little cobalt and nickel. The indications are that the Mississippi Valley is underlain by a basic magma.

The Tertiary magma belt of the Cordilleran region extends through South America, and in the other direction, around the Pacific, to the margins of Asia and to Australasia.

Of three major uplifts, since the pre-Cambrian, in the Cordilleran region, the last two—the post-Jurassic and the post-Cretaceous—were conspicuously attended by ore deposition. It seems likely, moreover, that the first and earliest of the major uplifts—the late Paleozoic-early Mesozoic, or Permian—may also have been signalized by ore deposition in Arizona and elsewhere. It is a very important ore-deposition period in Europe.

While epochs of ore deposition (metallogenetic epochs) are recurrent and periodic, they are not regular or rhythmic, but depend on a complex of factors.

A very recent metallogenetic province, like the last one (Pliocene) on the Pacific Coast, will show only the most superficial (quicksilver) zone of metallic deposition; one of intermediate age will show especially lead and zinc; and older ones will show copper, gold, and even tungsten, the difference depending to a great extent upon the depth of erosion, which is largely a function of time, and which has exposed the different ore zones accordingly. In Colorado, it is estimated that erosion has removed 5,000 to 10,000 feet of rocks since the deposition of the lead and zinc ores now outcropping; and we may by analogy assume a similar stripping by erosion from the lead-zinc deposits of the Mississippi Valley, a conclusion which is further supported by the known rate of erosion in the Mississippi Valley, and by a consideration of fault phenomena and the rate of faulting. These ores must have formed a long time ago, and within a brief period, for local post-mineral faulting evidently represents a long period of time.

Arizona is a wonderful example of the concentration of copper—constituting a metallographic province connected with igneous rocks. In the Helvetia and Bisbee districts, in Arizona, the copper ores are

probably of Permian age. In these districts there is evidence of long-continued erosion during the Triassic-Jurassic; and in Colorado, some hundreds of miles northeast, we find a series of rocks, especially red sandstones, of these periods, amounting to thousands of feet, evidently representing in part the ocean-deposited material won from the Arizona land-mass during these enormous periods.

Besides the probable Permian metallogenetic epoch in Arizona, there is a later metallogenetic epoch belonging to the post-Cretaceous epoch or revolution, as exhibited at Clifton-Morenci; and this is associated with monzonitic intrusions, while the observed cases of Permian ore deposits are associated with granitic intrusives. The post-Cretaceous group is abundantly represented in Arizona and New Mexico, not only by copper ores, but also by those of gold and silver, and lead and zinc. The lead-zinc ores are assumed, in accordance with the foregoing, to have formed at shallower depths than the copper ores, which are roughly assumed as formed at a depth of some 15,000 feet; one deposit of silver-lead ores in New Mexico is estimated by Lindgren to have formed 4,000 feet below the surface.

Nearly all the post-Cretaceous intrusives of this region are associated with the development, in the intruded limestones, of lime silicates, and, therefore, the associated metallic minerals have been classed as "contact-metamorphic" deposits, a term which I believe we should use very warily. Metallic minerals are not necessarily of the same age and formed at the same temperature as the associated lime silicates. Altogether, I feel that the classification of ore deposits by their metals, instead of by their non-metallic minerals, is the safer way. My experience is that metallic sulphides are generally later, and at a lower temperature, than lime-silicate crystallization. By an increase in rock temperature after ore deposition, it is, however, possible for lime silicates to be formed after metallic sulphides, and conceivably this may go so far as to transform these sulphides to (metamorphic) oxides and silicates. I am inclined to regard the zinc deposits at Franklin Furnace, New Jersey, as having this origin.

Sulphide orebodies, even when associated with basic igneous rocks, represent practically the latest stage of magmatic crystallization, and indeed the same stage as the sulphide ores associated with siliceous igneous rocks.

Besides the Permian and the post-Cretaceous metallogenetic epochs in Arizona, abundant copper was also precipitated at the time of the pre-Cambrian revolution, the vastest of the three. This is exemplified by the camp of Jerome, and others in Arizona and New Mexico. Finally, copper occurs representing still a fourth epoch—the late Tertiary.

Therefore, the remarkable thing about this southern Arizona region

is that there are important representatives of four great periods of ore deposition—pre-Cambrian, Permian, post-Cretaceous, and late Tertiary; and that the ore of each period was predominantly copper. We must admit that, at recurring brief periods, many millions of years apart, igneous-magma intrusion was accompanied by an ore-magma intrusion in which copper was relatively phenomenally abundant. Arizona, therefore, as indicated by the products of at least four distinct metallogenetic epochs, is a metallographic province.

CHAPTER X

Concerning Metallographic Provinces

A METALLOGRAPHIC PROVINCE is quite a distinct thing from a metallogenetic epoch, as developed in Chapter IX. I first described such provinces as "metalliferous," but changed the term to "metallographic" province. De Launay has used the designation "metallogenetic" or "metallogenic" to refer to provinces. His use of the term seems to be partly a geographic one—namely, a term used to designate certain geographic provinces which are ore-bearing. De Launay finds, in all these metalliferous provinces, veins having characteristics according to the depth of erosion, which he divides into the deep veins, the intermediate, and the superficial.

As for the origin of metallographic provinces, I am no longer willing, as I was once, to subscribe to the belief that they owe their origin to magmatic differentiation, as we understand the term. Differentiation in rock magmas is recorded by fact, and its existence is, therefore, not simply a theory. By differentiation arise chemical and mineralogical variations within a single rock; and thus, with sufficient circumstantial clarity to be satisfying to the geologist, arises the splitting up of magmas into submagmas varying widely in composition. Moreover, in volcanic regions, the succession of lavas corresponds to the theory of a magma splitting on a very large scale into complementary types, such as an andesite magma into rhyolite and basalt. But the evidence is that this differentiation takes place only after the accession or ascension to a certain subcrustal zone of a fresh supply of undifferentiated magma. During the Tertiary in Nevada, there were several such complete cycles of differentiation, probably three in number. This would imply a normal lack of differentiation at the ultimate source whence these recurrent invasions of magma are derived; and would, therefore, negative the hypothesis of universal processes of differentiation, resulting in petrographic or metallographic provinces.

It is widely held that the greater (oceanic) depressions and the

greater (continental) elevations of the earth's crust have been, relatively speaking, stable. Pendulum observations, and the study of rock analyses as well, show that oceanic areas have relatively greater specific gravity.

Considering the earth as a whole, we find that the rarer metals are distributed very unequally, and occur mainly in certain provinces. Thus, tin occurs especially in Bolivia, in the Malay Peninsula, and in the Dutch East Indies. It is always closely associated with siliceous igneous rocks, especially granites; but there are vast areas of granite which are not associated with tin. Tungsten is a common associate of tin, but there are many tungsten-bearing provinces which carry no tin whatever. Tin ore is more closely restricted in its occurrence than is tungsten, yet tin is estimated to be a relatively more important component of the earth's crust in general. Silver is less abundant in the crust than tin, yet its commercial occurrences are very widespread. Again, the commercial concentrations of gold, one of the least abundant elements in the crust, are distributed very widely. Vanadium is an example of high concentration, occurring especially in Peru and in the Rocky Mountains.

This selection by each metal of certain spots on the earth's crust for its concentration is difficult to explain; but it must mean that there exists in that portion of the earth which is below the crust exposed to our view by erosion, a highly individualized distribution of the metals. For this there is no better illustration than the remarkable Arizona copper-bearing metallographic province. The igneous rocks which accompany the ore deposits in Arizona are not restricted to Arizona alone; the late Tertiary lavas, for example, have an immense distribution all around the Pacific, yet only locally are they copper-bearing, as in Arizona. We must conclude that in the Arizona metallographic province the magma wave must have acquired some additional peculiarity not originally inherent in itself, but inherent in this particular spot of the earth's crust: in other words, that on reaching this spot it has experienced an addition of copper. This suggests an heterogeneous under-earth, which has remained stably heterogeneous during the whole of our geologic historical record; and this argues a prehistoric epoch of high earth fluidity and opportunities for chemical segregation.

We can reason out three crustal zones which have to do with ore deposits: First, the crust of consolidated rocks; second, and deeper, a magma zone; third, a still deeper zone which locally at least is a rich storehouse of certain metals. This lowest zone is stable; the superficial zone is stable in nature but unstable in position; and the intermediate zone is stable neither as to nature nor position. The intermediate zone is capable of two subdivisions: the upper, the zone

of differentiation and crystallization; the lower, where the magma flows but does not differentiate. This magma flow is the act which unlocks the treasure house of copper (as in Arizona) by contact or conjunction with the deep metalliferous zone; and ascension and differentiation of this enriched magma produces ore deposition.

Owing to the great specific gravity of the whole earth, as compared with that of its visible crust, it is widely held that the interior of the earth is largely metallic. Dr. H. S. Washington suggests that under the silicate crust lies a nickel-iron zone, of such material as is contained in certain meteorites, and that the heavier metals underlie, the heaviest being closest to the center. Geological evidence, however, seems to me opposed to the assumption of a universal nickel-rich layer or zone immediately beneath the silicate crust; the evidence is in favor of a metallic heterogeneity beneath the crust.

What appears to be a remarkable piece of additional evidence may be read from the "World Atlas of Commercial Geology," published by the United States Geological Survey (1921). On the chart showing silver production, we perceive that the great Mexican silver camps all lie in a straight line, or narrow straight zone, running northwest, and that this continues into Nevada—making a line 2,500 miles in length. If we extend this line straight southeast till it strikes the South American coast, we find that it coincides quite accurately with the great silver belt of Peru and Bolivia. This line, in North America, cuts diagonally across mountain ranges, and disregards geologic structure. What does this mean? We are tempted to define this straight belt as a structural feature, but one that plainly underlies the loftiest mountain chains and the magma reservoirs beneath them. Copper and other metals are present in this zone, but silver is the essential and conspicuous metal: the rich copper belt of Chile has a different trend, running north and south, and coinciding with the Andes uplift. Such long straight lines suggest the approximately straight lines which block out the continents as angular bodies; and the actually irregular coast lines appear to represent a later upholstering of these geometrical blocks.

In Colorado, there is a mineral belt, characterized especially by silver, running northeast across the State, and diagonally across the mountain ranges. There is a suggestion that as a mineral belt this may be very ancient, and not entirely post-Cretaceous, although most of the ores are of this age. This belt may, therefore, be of the same type as the Great Silver Channel which I have described above for North and South America; it runs at right angles to this channel. There is also a suspicion of a straight northwest-southeast belt of gold deposition in Alaska, independent of geologic structure. In Montana and Idaho there is a northeast-trending silver-gold belt, 500 miles long, parallel to

the Colorado belt; and intersecting or joining this Montana-Idaho belt there is a northwest-trending belt of great persistence.

In Utah, Butler has recognized the fact that the igneous rocks are arranged in definite east-west zones of great length. Folding and faulting accompanied the intrusion, and I believe resulted from the dynamic thrust of the intrusion; the axes of folding run north-and-south, at right angles to the intrusive zones, which I regard as evidencing eastwardly magma flow from the direction of the Pacific. Does not this evidence of eastwardly magma flow explain the general east-west strike of mineral veins in this region? The first fissures after intrusion determine, as pointed out in previous chapters, mineral veins; and observations show that in large measure they follow the major trend of the causal magma body; and if the latter were east-west in trend, the veins would conform.

Butler's geologic map of Utah shows an east-northeast belt of mining districts, about 150 miles long and 20 miles wide, cutting across the mountain uplifts, as do the intrusive rock zones.

The above sketchy data indicate the existence, in North America especially, of two sets of straight belts of silver deposition (with other metals) running respectively northeast and northwest. The major channel, which is of world proportions, parallels rudely the eastern side of the Pacific. All these belts are independent of geologic structure. These straight-line geometrical metal zones, therefore, probably belong to the stable under-earth, below the zone of magmas which stream landward from the ocean basins.

CHAPTER XI

Ore-Depositing Fluids Other Than the Ore Magmas

THE PREVIOUS CHAPTERS deal with what I believe to be the main manner of deposition of the relatively rarer metals; but there are many other manners. Every body of water that rests or circulates upon the earth, or in the rocks, is a dissolving and precipitating agent.

Into the oceans are brought mineral material in solution and in suspension; annually 2,735,000,000 tons of material are thus added to the oceans. Yet the ocean waters do not become saturated with mineral salts in solution, because precipitation is constantly going on, principally through organic agencies. The lime is precipitated, and eventually forms limestones. Some organisms precipitate silica, forming flint or chert; some precipitate iron, forming eventually great iron deposits, like those of the Lake Superior region. Manganese is also precipitated in this way, and even iodine and potash.

Also, mineral concentrations are effected in smaller bodies of water—in lakes, lagoons, and bogs, either through organic agencies or through more direct chemical methods, chiefly on account of drying up of the waters. Iron and manganese are largely precipitated through organic agencies. Through evaporation are deposited large amounts of sodium, potassium, magnesium, and lime salts, producing the great salt and potash deposits of the world.

The atmospheric water circulating through the rocks—the ground water—is active in dissolving and precipitating. The carrying off of more soluble elements leaves the less soluble as a concentrate, or residual deposit. Thus are formed, from original feldspathic igneous rocks, important deposits of kaolin; and of bauxite, the principal ore of aluminum. Some manganese deposits are formed in this way; also, phosphate of lime; and some deposits of magnesite.

It is the very commonest elements in the earth's crust whose principal commercial deposits are formed by surface waters. Of the rarer elements there is none which does not owe its chief commercial concentration (as primary ore) to magma action. The concentration of these elements into important or primary ore deposits seems to be beyond the power of superficial agencies, and earlier beliefs to the contrary are being progressively overturned.

The surface waters are potent in mechanical concentration: and thus arise placer deposits, of gold, platinum, zircon, monazite, some iron; and practically all our commercial deposits of silica.

The work of superficial concentration is done in the zone of chemical reactions between the atmosphere and the solid crust; and the most powerful chemical agent is living organic matter. What do the surface waters accomplish below the zone of chemical reactions between the atmosphere and the rocks? To the best of my belief, little or nothing. The great mass of rocks is not searched by ground waters, as we once imagined, and their daintiest and tiniest treasures, like gold and silver, robbed and amassed. If veins were formed by this uniformitarian process, we should find metal veins in all stages of growth in all rocks. Nor do I believe that ascending artesian waters are effective causes of metal concentration.

Now, about hot springs—we conceive of these as of magmatic or atmospheric origin, or both mixed. They contain abundant mineral elements in solution, and deposit silica and lime on coming into contact with the air, but do not thus form metallic precipitates of commercial value, though in some cases traces of metals are deposited. Do these hot waters form mineral veins below the surface? We have little evidence concerning this; where we encounter them underground, we find them leaching, not precipitating. Hot springs of magmatic origin are closely allied to the emanations in volcanic craters—fumaroles.

Fumaroles, on reaching the atmosphere, form commercial deposits of sulphur, boric acid, ammonium chloride, potash alum, and other mineral substances. They frequently carry traces of many metals, but form no commercial deposits of any metal. Deposits like borax show a magmatic origin for these fumarolic deposits; and the presence of considerable boron in hot-spring waters may be taken as an index of the magmatic origin of the water. Are these waters, then, the magmatic fluid from which magmatic metalliferous ores have been deposited? The evidence is that cinnabar (mercury) is really deposited from such hot waters, at around 100° C., with chalcedonic silica, barite, gypsum, and rare fluorite; and some stibnite. Certain ore deposits seem related to these, such as the deposits of gold, realgar, and cinnabar at Mercur, Utah, and the similar deposit of the White Caps mine, at Manhattan, Nevada.

While silica and other earthy elements occur in these hot springs, they form at most only a very small amount relative to that of water; at Steamboat Springs, for example, only 2.85 parts per thousand. These solutions must be far different from the siliceous or other magma solutions which in earlier chapters we have found to have penetrated the rocks as veindikes, usually without any crustification, although even certain well-banded veins must, I believe, have formed from highly saturated ore magmas, entirely different from the hot-spring waters, since these veins frequently inclose angular unsupported fragments of the wall rock. Therefore, I conclude that even these hot-spring waters of magmatic origin do not represent the typical ore magmas which have formed veins in depth, but are perhaps the aqueous residue from such magmas. These aqueous residues (hot-spring waters) do, however, probably form cinnabar deposits, and some other unusual deposits; but I believe they are inert and do not deposit even these special types of mineral deposits unless they are residual from ore magmas, and not merely, as is usual, from rock magmas.

The fine rhythmic banding in certain mineral veins is probably usually not due to gradual filling of a fissure from circulating waters, but indicates a pulsating deposition from a standing solution, which stands in and fills the fissure during this period. These veins often carry angular unsupported fragments, indicating that the fluid had high specific gravity, or viscosity, or unequal gaseous-tension pressure, or all. Rhythmic banding of the kind found in these veins has been observed to occur in a gel or jelly. A silica jelly contains about 14 per cent SiO_2; but some ore magmas, I believe, have much less water than this indicates—some are more and some less aqueous.

In a siliceous vein magma, I believe that on consolidation there is a constant tendency for the silica to crystallize first, the metallic minerals

subsequently. This law explains many ore occurrences. The later highly metallic stages may occur within the siliceous veins, or in their walls, or as independent veins or veinlets.

In résumé, I see two great classes of ore deposits—the one characteristic of the atmosphere-rock contact zone, and marked by large concentrations of the commoner elements; the other the result of magma differentiation, and marked by concentrations of all the elements, whether common or rare.

There remains to be considered the modifying or secondary effect of various fluids on primary ore deposits. Ordinary surface waters are very potent in this rôle, but only in the atmosphere-rock contact zone. Oxygen breaks up the original mineral combinations, and a rearrangement is effected by descending surface waters, the completeness of which depends upon the metal. Copper is very easily dissolved and reprecipitated under these conditions, and this process results in enriched copper ores, of vast commercial importance. Silver ores are worked over to a less extent, and lead and zinc ores are notably affected, the lead and zinc being frequently dissociated in the process. The fact, however, that in all these cases the primary ores beneath the effects of oxidation are quite unmodified by ground waters is in effect a demonstration of the correctness of my conclusion of the inability of ground waters to form primary ore deposits.

Shallow waters may also move upward in hot, dry regions, and evaporate at the surface, depositing their mineral load. This forms crusts of salt, soda, or borax in the Western "alkali flats," enriches outcrops in the desert, and even old ore faces in mines.

What is the effect of ascending hot waters in working over primary ore deposits? They should be more potent than cold waters. They do not contain oxygen, but they do contain other active reagents; and it is altogether likely that they may effect considerable concentration where they traverse already-formed deposits. Ferguson describes at the White Caps mine, at Manhattan, Nevada, an example of deposition of realgar and stibnite probably from solutions of this type, perhaps partly from the working over of an earlier auriferous arsenopyrite deposit. Arsenopyrite appears unstable in such solutions, and realgar the stable form of arsenic sulphide; and the same thing seems to apply to known hot springs and volcanic fumaroles; while arsenopyrite is characteristic of ores deposited from the ore magmas properly speaking, and is formed under greater pressure. Similarly, stibnite seems to be the characteristic antimony mineral for hot-spring waters, while from ore magmas more complex sulphides, combinations of antimony with copper and lead—like tetrahedrite and jamesonite—seem typically formed.

Ores deposited from the true ore magmas have formed close to

the surface, as at Tonopah, where the variety of metallic sulphides show a high and varying temperature. How near the surface did they form, and did they reach the surface? Rock magmas do reach the surface; but quartz veins, or quartz-carbonate veins, the commonest gangues of magmatic ores, do not reach the surface; none are reported from the cooled surface of any recent volcanic center, and the same is true of the magmatic ore deposits in general. Between the fumarolic deposits of the surface, therefore, and the vein deposits formed at a certain depth, there is a marked distinction. Note, also, that only certain volcanoes show metallic sublimates, just as ore deposits are found only in association with occasional intrusive igneous rocks. Ore deposits are now doubtless in process of formation—we are within a metallogenetic epoch; and we can perhaps partly judge where they are forming from the character of the sublimates in existing volcanoes.

To study the problem further we may examine slightly eroded volcanoes and volcanic rocks. And, to be sure, the great majority of these show no metallic deposits, while a few show deposits which may be very rich. Cripple Creek, Colorado, is an example, where the ores were formed at depths estimated at from a few hundred feet to 3,000 feet. Why do not such solutions appear at the surface, and there form ores of unparalleled richness? The fact that they do not leads to a strong assumption that they cannot. Why can they not? It is hardly a question of temperature, for volcanic fumaroles are in part very hot. Apparently, therefore, it is a matter of pressure; above a certain depth, the ore magma cannot retain the gaseous elements, which dissociate themselves and escape, and thereby cause the precipitation of the metals and gangue in solution. This critical upper-pressure limit appears to be less than 1,000 feet from the surface. The Carmen mine, in Guanajuato, Mexico, appears to represent the top of the ore zone, and possibly the Divide mine, near Tonopah, Nevada. The Bassick ore deposit in Colorado, in a volcanic neck, cannot have formed many hundreds of feet below the surface; and both here and at Cripple Creek ore deposition was a sharply defined geologic event, a stage, apparently, of a magmatic-differentiation series, marked otherwise by a succession of emissions of different lavas. The occurrences at Cripple Creek and in the Bassick mine prove that ore deposits in volcanic rocks near the surface are magmatic-differentiation phenomena, and that they ascend from the magmatic laboratory at great depth.

I conclude, therefore, that ore deposits may be formed within, say, 500 feet of the surface, by an ore magma derived from magmatic differentiation, and ascended from the depths; but that at this critical pressure zone the ore magma disintegrates, and the metals and earthy

elements in solution are precipitated. This is analogous to what takes place in depth, but more gradually. Where the consolidation takes place in depth, the aqueous residual vapor may ascend to the surface as hot springs, depositing mercury, arsenic, and antimony: where it occurs close to the surface, the vapors may appear at the surface as fumaroles, which deposit metallic minerals.

CHAPTER XII

The Derivation of Certain Ores from Certain Kinds of Igneous Magmas

CERTAIN METAL DEPOSITS cling closely to certain kinds of igneous rocks: for example, chrome ore is associated exclusively with very basic rocks; tin ore exclusively with siliceous rocks. Tin ore is at home with granites; chromite with peridotites. The tin oxide forms later than the granites—as the last phase of the magma. The chromium oxide, on the other hand, has usually been held to be older than the silicates of the peridotites. There is some doubt about this, as in the case of magnetite, which has been similarly so held. Magnetite in igneous rocks is not necessarily a crystallization from a melt, but is often demonstrated to be a deposit from a residual fluid magma. Observations by Ball and myself in Colorado show that in the case of magnetiferous granites, the magnetite was a mineral of the pegmatite stage.

The old test of perfect crystal outline, or "idiomorphism," is not a true test of earlier crystallization: for such crystals may develop last, by replacement of older ones, and represent the pegmatite stage. Such may be the case with minerals like zircon, apatite, or pyrite. Chromite, however, does not occur in the pegmatites; it is more like ilmenite, which rarely so occurs, than like magnetite, which frequently so occurs. Chromite is apparently not soluble in the gaseous elements of magmas. Among the minerals characteristic of basic rocks, chromite is associated with olivene rocks, ilmenite with lime-soda feldspar rocks. Evidently, chromium is soluble only in a concentrated magnesia-lime-iron magma, while titanium is not soluble in this, but is soluble in a somewhat more siliceous magma, containing a great deal of alumina.

Characteristic of the basic rocks only is also nickel; of the siliceous rocks only are also tungsten and molybdenum. The order of crystallization for ore deposits and igneous rocks alike appears in general to be: silicates, oxides, sulphides. Nickel occurs as a sulphide, while chromite, ilmenite, magnetite, and specular iron are oxides. Nickel is often closely associated with copper and iron sulphides, as at Sudbury,

Canada; but copper is not confined to basic rocks. Platinum, however, is practically so confined.

Duparc and Tekonowitch have described the platinum of the Ural Mountains. The mother rock is dunite, or olivene rock. The dunite is typically in a rudely elliptical outcrop, around which is a shell of pyroxenite, and around this an outer shell of gabbro. Magnetite (frequently titaniferous) is characteristic of the pyroxenite, as chromite is of the dunite. Platinum is closely associated with the chromite.

The circumstance of the dunite "centers," surrounded by shells of pyroxenite and outer rings of gabbro, is also duplicated in British Columbia and elsewhere. Clearly these represent intrusive domes, differentiated after intrusion. Differentiation has been made possible only by magma migration into an upper zone. The succession of rings or shells might suggest gravity as the cause of differentiation, but this explanation finds insuperable obstacles in fact. The fact is that the first-formed minerals (olivene) form the core, the latest silicates the outer shell. The distributing or differentiating force I postulate to be *gaseous tension* in the magmas, which I have already appealed to as the intrusive force also. The rule, to which exceptions may be noted, would be that the siliceous rocks (and, of course, most of the metallic ores) would differentiate to the outer rim of magma bodies. Therefore, intrusive granite domes, which do not show this differentiation into shells, may represent the upper, differentiated shell of an originally intermediate-basic intrusive magma dome of vaster dimensions. Thus, the time for complete differentiation may be long or short, depending upon local conditions.

The close association of chromite with olivene indicates that its vapor tension and fluidity is, like olivene, easily lost at a still high temperature, so that it congeals. Likewise, ilmenite must have a vapor tension and freezing point close to that of pyroxene. But magnetite must have a higher and more permanent vapor tension; for it travels further, and is found not only in basic rocks but in intermediate and siliceous ones, and even accumulates to a notable degree in the wall rocks.

Nickel sulphides in basic rocks, associated with copper sulphides, form a type which passes over into copper deposits in or near basic rocks, but without nickel. These copper deposits tend to form sulphides high in copper and low in sulphur, a tendency which ends in the entire loss of sulphur, and the deposition of native copper. Such copper deposits, as in Michigan, contain arsenides of copper, nickel, and cobalt, and some silver; and so are transitional into rich silver ores, often carrying much native silver. A step further than this is probably afforded by the lead-zinc deposits of the Mississippi Valley.

In all this series the gangue minerals are scanty; calcite is as representative as quartz, or more so; there is apt to be a scarcity of

primary sulphur; and zeolites mark many of the copper deposits. Thus we have a basic-magma-derived ore sequence, which we may compare with the known siliceous-magma-derived ore sequence. In both sequences we have chalcopyrite, arsenical ores, blende, and galena. Plainly, the residual magmas from basic magmas are poorer in silica and the gaseous elements than those derived from siliceous magmas; and we are surprised to find that the paucity of "mineralizers" does not militate against the richness of basic-magma-derived ores.

Siliceous-magma-derived ore magmas are plainly not only siliceous but alkaline; hence these alter the wall rocks more than those of the basic-derived type, and attack, especially, basic rocks. Basic-magma-derived ore magmas frequently attack the wall rock very little, showing in some cases a relatively dry fluid sulphide magma, with a striking lack of "mineralizers."

In classifying ore deposits, therefore, I feel that in general only a subordinate importance should be attached to gangue minerals: that the presence or absence of minerals indicating the abundant presence of the gaseous elements (known sometimes as "mineralizers") is of very little significance, except as to their diagnostic value above noted.

Besides the basic-magma-derived ores and the siliceous-magma-derived ores, it appears that ores may also be derived from intermediate magmas, and the ores resulting from these will be intermediate in nature

CHAPTER XIII

The Three Main Lines of Descent for Ore Deposits

GOLD HAS NOT BEEN concentrated from basic magmas; on the other hand, it is curiously absent from the typical siliceous-magma-derived ores, such as tin and tungsten. The main succession of metals, with falling temperature, from the basic magma is: chromium, nickel, copper, zinc, lead, and silver. From the very siliceous magma it is tin, tungsten, copper, zinc, lead, and silver; this is the succession in Cornwall and also in Tasmania. In Bolivia tin veins have formed at high temperatures, and later silver veins at moderate temperatures, with the intervening metallic stages not well represented. The tin-ore formations are not confined to any one geologic period: the tin of Bolivia is in part at least late Tertiary; that of Tasmania is Devonian; that of Cornwall marks the division between the Carboniferous and the Triassic; in the Malay States, the tin is post-Triassic; but all are connected with granitic rocks.

Now, the ore sequences in none of these instances include gold; but in most of the sequences I have described in western North America,

gold is important, and one important gold-bearing stage is deep-seated, so that we have the general sequence: gold, copper, zinc, lead, silver. Therefore, the gold-bearing magma must be distinct from the tin-bearing magma; and I accordingly suppose the derivation of the gold ores from an intermediate magma type. We have, then, three chief lines of ore descent—from the basic magmas, the intermediate magmas, and the siliceous magmas, to all of which the sequence copper, zinc, lead, and silver is common: the difference is in the higher-temperature minerals, and the key minerals of each group are, respectively, nickel, gold, and tin: the first two, but probably not tin, also recur in a minor way in the sequence, at lower temperatures. The last two also occur in a minor way in volcanic rocks; but this is not true of nickel, or indeed of its basic magma-sequence associates, platinum and chromium.

Like gold, silver is not wholly static, and confined to its normal zone in the sequence; but, like gold, occurs at three distinct pressure-temperature horizons. Neither is molybdenum wholly static. But copper, lead, and zinc appear to be static, and confined to one major pressure-temperature zone. It is to be noted that the occurrences of gold above its characteristic deep high-temperature zone are associated with arsenic, which has apparently acted as a carrier. Arsenic itself is not static, but recurrent, in all three vein sequences—basic, intermediate, and siliceous; and the same is true of antimony. In this class of highly mobile metals which act as carriers come tellurium and selenium. Probably gaseous elements like fluorine, chlorine, and boron have a much less importance as carriers of metals, or mineralizers, than do these mobile metals. The effects of these gases is most noticeable in the siliceous and intermediate rock magmas; and though they seem to be insignificant in the basic magma residues, ore deposition goes on without any consequent handicap.

Consideration of occurrences, representing these various types of ore deposits, indicates that the typical basic-magma-derived ore-magma solution is calcic, non-siliceous, and with scanty excess material over the metallic sulphides, whether this excess material be earthy constituents, water, or gaseous elements (including sulphur); while the siliceous-magma-derived ore-solution magma is siliceous, aqueous, and non-calcic; and the ore magmas of intermediate derivation have intermediate characteristics.

Another problem is the frequent association of hydrous lime silicates with basic-magma copper deposits; and of non-hydrous lime silicates with siliceous-intermediate-magma copper deposits. In the first case, the lime silicates appear to be due mainly to the reaction of calcic solutions on silica in rocks; in the latter, mainly to the reaction of

siliceous solutions on lime in rocks; but why the water in the silicates in the former case?

CHAPTER XIV

Calcic Metamorphosing Solutions on Intermediate Rock Contacts

THE LAST CHAPTER SHOWED that the earthy-gangue materials, whether quartz or calcite, are not an essential part of the ore magmas; moreover, that waters and other gases like fluorine, boron, etc., are really necessary, if at all, only in very small relative amounts. It was shown that basic-magma-derived ore magmas are calcic; the siliceous equivalent, siliceous; and consequently the intermediate-magma-derived ore magmas are siliceous-calcic. Such a siliceous-calcic residual solution may have its silica removed by reaction with limestone, leaving it wholly calcic.

At the Bonanza mine, in Zacatecas, in Mexico, there is an excellent example of the last. Here monzonite has intruded Mesozoic limestones, and lead ores have formed along slight fissures in the limestone near the contact. The ores are not in any way associated with lime silicates, being of later age. The whole limestone has been recrystallized or marbleized in a broad belt between the contact and a parallel belt of shale: beyond the shale the limestone has not been recrystallized. On the exact border of the intrusive monzonite, in a regular belt 50 to 100 feet wide, the monzonite has been changed to lime silicates, but the limestone comes up to the exact igneous contact with no alteration to lime silicates whatever! Here is a reversal of what we usually expect; and it indicates that lime has metamorphosed the monzonite. The hot metamorphosing solutions plainly were calcic, and not siliceous; therefore, they did not alter the chemical composition of the limestone, but recrystallized and bleached it: but they calcified the monzonite on its border. They also metamorphosed the shale on the other side of the recrystallized limestone belt (in which belt lie the sulphide ores) for a width of 150 feet or so, on the side facing the belt, but not on the other side.

We must, therefore, grasp the truth that the metamorphic lime-silicate rocks are due to a great and uncharted range of solutions. At Helvetia, in Arizona, for example, we have evidence of at least four chemically different successively acting types of metamorphosing solutions.

The Aranzazu mine of the Mazapil Copper Company is some miles from the Bonanza, and occurs under the same general geological conditions, the ores being chiefly of copper and zinc; and here the evidence is that lime silicates have been formed by siliceous solutions.

A case somewhat similar to the Bonanza is probably that of the White Knob Copper mine, in Idaho, described by Umpleby. Here granite porphyry is intrusive into limestone; and while lime silicates have not been formed in the limestone, they have been extensively so formed in the granite. Calcic solutions are here again clearly indicated. In these cases the original residual solution was siliceous, or siliceous-calcic, but became purely calcic by reaction with limestone at greater depth.

The Copper Queen mine area, at Velardeña, shows alteration of monzonite to lime silicates; indeed, near the ore deposits, it is a question whether any of the lime-silicate rock has been formed at the expense of the limestone, indicating here calcic solutions; but in an area at a little distance away, the alteration of limestone to lime silicates by siliceous solutions, probably at a different stage, is indicated. The Descubridora mine, in Durango, Mexico, is a copper mine of similar type, where the sequence of events was: 1, intrusion of monzonite into limestone; 2, partial differentiation of monzonite; 3, consolidation of monzonite; 4, alteration to lime silicates; 5, formation of fissures; 6, intrusion of aplitic dikes; 7, ore deposition. Near the mine, the bulk of the lime silicates is confined to a monzonite-limestone contact which is barren of ores; here the alteration of monzonite suggests calcic solutions. The ore deposits are confined to a parallel fissure-contact of monzonite and limestone 800 feet distant, and are accompanied by very little lime silication.

CHAPTER XV

The Precipitation of Ore Magmas

IN THE PRECEDING CHAPTERS I have discussed the precipitation or crystallization of ore magmas, and the succession of ore zones, as a simple function of temperature and pressure. But there actually enter other elements: the heterogeneity of wall rocks, and solutions which the ore-magma solutions may encounter. These diverse rocks, and foreign solutions, by reaction with the ore-magma solutions, may considerably modify the stage and locality of ore depositions.

For effective reactions, the meeting of unlike substances or solutions is necessary. Therefore, the ore solutions of the siliceous type would be precipitated mainly by basic rocks and minerals, or by limestone. Thus, copper, silver, and gold are noticeably precipitated by basic igneous rocks, by limestone, and by carbonaceous material. Vanadium has apparently been precipitated and concentrated by asphaltite in Peru. In the same country, cinnabar (mercury) has been notably precipitated by bituminous material; and the same is the case with

important cinnabar deposits in California and Jugoslavia. Graphite occurs with the ores of Silver Islet, Ontario, and Ducktown, Tennessee. Also, we find graphite in quartz veins, and in pegmatite veins or veindikes.

Carbon in the form of carbonized wood has, in Utah, Colorado, and Texas, precipitated vanadium, copper, and silver; and in the form of oil shale, or bituminous limestones, has precipitated lead and zinc in Virginia and in the Mississippi Valley; and carbonaceous shale has precipitated gold in Australia.

Limestones react powerfully to siliceous-alkaline ore solutions and form replacement deposits of lead, zinc, copper, silver, and sometimes gold.

Very important is the precipitating effect on ore-magma solutions of mingling with other solutions. Sometimes ore-magma solutions representing different stages and traveling along separate fissures may meet and mingle. This is the case in the Eden mine, in Nicaragua, where the ores are in fissure veins in Tertiary andesite. There are two sets of veins running at right angles, and also two kinds of veins, though each kind is represented in both sets or directions. One kind consists mainly of sulphides—pyrite, chalcopyrite, galena, and blende—is auriferous and has only a moderate amount of gray quartz. The other kind is of white barren quartz, with practically no sulphides and only a little gold.

Taking the sulphide veins, we find they form branching fissure veins, where the branches join at angles of 25 to 30°. Examination of the ores in these joining fissures demonstrates that the different fissures carried different solutions. One type of solution carried silica, iron and copper, lead and zinc, sulphur, and a little gold; the other was a cooler solution of uncertain nature. When these two solutions, traveling along different fissures, met and mingled, the lead, zinc, and gold were thrown down, but not otherwise. Here the temperature is judged to have been near that of copper deposition; but the mingling of the solutions brought down the other metals noted The enriched ore goes upward some distance from junctions as seen on a vertical section, showing an upward flow of ore solutions.

Similarly, the Tecolotes mine, at Santa Barbara, Mexico, shows the effects of two distinct chemical types of ore-magma solution, flowing contemporaneously along different fissures, and, where they converge and unite, causing the precipitation of orebodies along the trunk vein where they have mingled. The ores of the distinct and separate vein types do not indicate solutions as radically different as those at the Eden. Both belong to the general galena-blende zone. One type of solution contained much more fluorine, more gold, less lead, much

less zinc, less copper, and about the same silver, as compared with the other. Both types of solutions filled open fissures, which they apparently distended and kept open by their own pressure; and where they met and mingled, much precipitation of both solutions took place. These two instances—the Eden and the Tecolotes mines—show only one period of fissure-filling.

Therefore, what appear to be branching veins are often really uniting veins.

At the Silver Lake mine, at Silverton, Colorado, are oreshoots dependent on fissure junctions, and the same types of solutions as at the Eden are indicated. Here, at the Silver Lake mine, the fissures were successively reopened and cemented anew by vein material; and this shows a progressive change in the nature of the circulating solutions, which deposited: 1, lead-silver ores; 2, gold-copper-silver ores; 3, mixed earthy carbonates; 4, quartz; 5, calcite. Usually all these stages, by virtue of successive reopenings of a single fissure, lie side by side, or intermingled, making a compound vein. Yet there was an intermediate stage when the solutions representing the No. 1 and the No. 2 vein types were contemporaneous, when they met and mingled, and formed oreshoots through the precipitation thus brought on.

The Pony Express mine, at Ouray, Colorado, shows fissure veins in Carboniferous and Mesozoic sedimentary rocks, overlain by Tertiary volcanics, all of which rocks are cut by intrusive dikes and sheets of porphyry. Directly after the porphyry came the fissure veins, of the formation of which three distinct stages are exhibited in the compound Bachelor vein. The first stage was a vein or veindike of barite, mixed earthy carbonates, and silver sulphides and sulphantimonides. The second stage, strange to say, was a mud veindike; the third was of blende, pyrite, and galena poor in silver; and the fourth fissuring was never filled. Where this composite (compound) vein splits, one branch, the Neodesha vein, is exclusively of the barite-silver-sulphide stage, while the other, the Pony Express, is exclusively the galena-blende-pyrite stage, low in silver. But there was no enrichment at the junction of the two vein types; which shows that junctions of vein branches do not necessarily create enrichment, unless they bring about the mingling of different magmatic solutions, or unless some other specially favorable conditions for precipitation are created by the junction. Similarly, at the Camp Bird mine, at Ouray, the main vein is a compound one, representing different stages or periods: the first, the deposition of argentiferous galena, blende, and pyrite; the second, quartz carrying much free gold. These veins branch, but there is no enrichment at the junctions, even when two types come together; and for the reason given above.

At Aurora, Nevada, are interesting, wide gold-quartz veins in Tertiary andesite. Clearly, these are intrusive veindikes, of a very common type in Nevada. Such veins carry gold and silver in all ratios in different districts; even those at Aurora vary from: gold to silver, 1 to 2 or 3 by weight, to 1 to 46 by weight. In these great veins there may be a slightly greater gold precipitation in the general vicinity of certain vein junctions, and the veins are not workable except for these shoots. This indicates the confluence of slightly differing solutions along different fissure channels. However, richer ore may apparently be formed in another way, by what I may call differentiation within the congealing veindike. In this way, richer streaks form on the walls, which is a phenomenon I have also observed at Tonopah; or within the vein. To account for this I am again led to appeal to differential gaseous tension within the veindike quartz-ore magma.

Many ore sequences in the intermediate and upper zones seem to show the reversed sequence of ore zones, as at Aspen, Tiro General, Silver Lake, and the Pony Express, indicating ore deposition during a period of rising temperature, which reversal of normal conditions seems accordingly more frequent in the relatively shallow depths. Now, in many mining districts the last magmatic stage is calcite fissure veins. But a reversal of temperature and vein sequence would superimpose metalliferous quartz veins upon the calcite veins; and instead of the latter lying alongside or mixing with the former, as in the typical compound vein, it would naturally replace the former. And this is indeed a very common phenomenon in the Tertiary shallow-formed veins; as, for example, at El Oro, in Mexico, where different veins show all stages between calcite and a complete replacement of the calcite by gold-and-silver-bearing quartz. Such instances are extremely common in Mexico and Nevada.

Exactly the same stages of metallic vein formation take place in the Tertiary lavas as at intermediate or great depths. But in the typical sequences, the uppermost zone is a silver zone, and next below come the lead, zinc, and copper zones. Therefore, the superficial Tertiary quartz veins, carrying much gold as well as silver, evidently testify to unusual conditions at this shallow zone, not applying to the deeper zones; and this implies the mingling, with the normal silver-bearing solutions, of gold-bearing solutions in all proportions, making a mixed siliceous ore magma. The gold-bearing solutions are probably of a superficial type, like those which formed the gold ores at Mercur, in Utah, and represent in some way the escapement of gold from the ore magmas, possibly under conditions of unusual relief of pressure on nearing the surface.

CHAPTER XVI

The Origin of Fissure Veins

I HAVE ASSUMED THAT MAGMAS are in a state of gaseous tension, by virtue of which they differentiate and by virtue of which they possess intrusive power; and this applies not only to the common rock magmas, but to the highly specialized magmas which I have called ore magmas. I have argued that a considerable proportion of the mineral veins are veindikes—that is, that they are intruded under their own gaseous tension. This is true of deep-seated veindikes like pegmatites, gold-quartz, tungsten-quartz, and tin-quartz veins, and also of the wide quartz veins in Tertiary lavas. On the other hand, many veins have formed by replacement or impregnation along fracture zones, indicating a thinner and more aqueous ore magma. But even veindikes have had their course and form determined by pre-existing fissures; and therefore we must study the laws of strain and fracture in rocks. The branching and reuniting, or "linked-vein," type appears to be characteristic of veins formed near the surface. The veins at Tonopah, Nevada, offer examples of replacement veins along fracture zones and also of intrusive veindikes; and there are transitions indicated between the two types, or between highly aqueous and slightly aqueous vein magmas. Certain calcite veins at Tonopah are limited to a rhyolite volcanic neck, showing the dependence of the locus of the veins on stresses set up by the adjustments of the igneous rock after intrusion.

At Velardeña, in Mexico, the Terneras group of veins lie in an elongated mass or neck of intrusive dioritic rock, and run across the intrusion from side to side. When they enter the intruded limestone on either side, they weaken and disappear. It is probable that the vein fissures were due to post-intrusion adjustments in the diorite mass; that the ore-magma solutions were derived in depth from the same source as the diorite; also that the ore magma was dry and aplitic. The vein fissures have been repeatedly opened, and each time filled by new materials; some of the fillings are veindikes, and inclose isolated angular fragments of the wall rocks.

The Santa Maria group of veins at Velardeña occur in connection with a dike of trachytic alaskite, intrusive into limestone. There has been subsequent movement along the contacts of the dike, and parallel fissures developed in the limestone; along these the ore materials—galena, blende, and pyrite—have penetrated both by infilling and by replacement. The lack of extensive replacement of the limestone here also shows a slightly aqueous ore magma.

The Guardarraya group of veins at Velardeña is associated with

irregular intrusions of dioritic rock, and the veins follow definite but not very persistent fractures near and roughly paralleling the contact and sometimes transverse to it; they lie partly in the igneous rock and partly in the limestone. These fractures, also, evidently resulted from the adjustments of the intrusive rock after intrusion; and in the case of some of these veins the lack of marked replacement of the limestone indicates a relatively dry ore magma, while others have replaced limestone, and so were more aqueous.

Lime silicates have formed in or near the intrusive rock in the case of all three of these groups of veins at Velardeña; but the lime-silicate formation has no close connection with the mineral-vein formation.

In the Matehuala district, in Mexico, in the main ore-producing area, there has been an irregular intrusion, into limestone, of monzonite, with a northwest axis of about 3,000 feet, and a northeast width of 600 feet. Some of the ores occur at the intrusive contact, yet mostly along fissures which have there developed. Within the monzonite are two sets of fissure veins, about equally strong, one set parallel to the long axis of the intrusion, and one transverse to it. There is no faulting along these fissures—they are plainly due to contraction strains. Some of these fissures carry ore only where they intersect the contact, and there they have deposited sulphides by reaction with the limestone, showing one way in which a pipe or chimney of ore may originate.

All the Matehuala vein stages were evidently from ore solutions far more aqueous than most of those at Velardeña. This may be due to the more basic character of the magma at Velardeña (see Chapter XIII). Note here, again, that only those cracks and incipient faults formed first after the intrusion have served as channels for the making of fissure veins; then the brief period of ore deposition or ore intrusion—definite, in the geologic sense, as dike intrusion—was over for good and all, and later deeper fissures are barren and empty.

Veins very commonly form along dikes, simply because the fissure filled by the dike remains a line of weakness, and reopens preferentially. This persistent weakness of fissures, even though filled or cemented, is the reason for compound veins, which are the result of repeated openings and fillings at different stages of the ore-magma precipitation.

Many veins, of course, are not in igneous rocks; but when they are near intrusions, it is nevertheless likely that the fissures which have invited them have been mainly due to adjustments of the igneous mass after intrusion; and the fissure systems arising in this way may be various.

If the localization of ores in fissures of slight or no displacement is the rule, how shall we explain the common exception, where fissure veins fill faults of considerable magnitude? At Peñoles, in Mexico, is a heavy fault whose origin was early, though the date is not fixed.

An earlier set of veins—blende-galena-arsenopyrite-cupriferous pyrite—filled these fissures at one stage; and at or just preceding a far later volcanic period silver-quartz veins again occupied these reopened fissures; and after continued faulting, calcite-siderite veins; and after this the faulting continued, resulting in empty fissure fractures. Considering only the amount of faulting which immediately preceded the silver-quartz veins, the case probably comes within the rule of vein-filling after fissuring of slight displacement. Veins which fill a fault fissure of an origin more ancient than the igneous epoch of which the veins are a phase, I dub immigrant veins; while those that follow the more usual rule I call domestic veins.

A special case is represented by Aspen, in Colorado, where the ore deposition arrived only after considerable faulting, and there is also much subsequent faulting. In one case noted, the Clark fault had a pre-ore displacement of 250 to 350 feet; then came the brief period of ore deposition; then, along the fault, a post-ore displacement of 400 feet. The stages of ore deposition at Aspen (1, barite; 2, rich silver sulphides; 3, galena and blende) are reversed from the normal sequence, and hence indicate a rising temperature, which I have referred to a rising magma plug below. This may explain the considerable pre-ore faulting, as due to the upward shove of the magma, in contrast to the post-intrusion adjustment faulting which is so commonly indicated; in which case the post-ore faulting at Aspen would probably still be of this upward-shoving origin, an explanation which is certainly indicated, as I have shown, for some of the most striking of the Aspen faults, where the faulting progressed apparently more or less in measure with the stripping off by erosion of the rock load.

Two types of faulting resulting from intrusion are then certain, that resulting from excess of the uplifting telluric pressure, and that resulting from excess of the gravitational adjustment pressure: these two types we may name intrusion faulting and adjustment faulting. Either type of faulting may act horizontally as well as vertically. Igneous intrusions, as demonstrated at Tonopah, seem to have a tendency to approach the surface at an angle, often very flat, instead of coming straight up. Some of the Western thrust faults may be an example of intrusion faulting by such flat-moving upward intrusions.

Upon the consolidation of an intrusion, the magma loses in volume, and the intruded rocks close in as this takes place, resulting in slight adjustments of these intruded rocks, which in the case of irregularly shaped intrusions will result in many fault fissures of very slight displacement, with a large horizontal component of movement, which will tend toward division into "conjugated" sets, dipping in opposite directions.

Viewed in this broad light, nearly all faulting may be due to the effects of magma migration—direct and indirect.

The condition of veins occupying fissures of slight displacement in a horizontal direction is a very common one: as at Georgetown, in Colorado, where the fault striæ approach the horizontal. But at Idaho Springs, near by, the differential movement averages 60° from the horizontal. The Georgetown veins are silver-lead-zinc; the Idaho Springs veins, gold-pyrite ores. The former are connected with monzonite intrusions; the latter with more alkaline intrusions, both intrusive in a pre-Cambrian complex. Study of the work of myself, Ball, and Garrey, together with that of Bastin and Hill in the northeast extension of the belt, indicates that ore deposition in these regions is a magmatic episode or episodes, and the ore magmas and the various dike magmas were alike phases of the mother quartz-monzonite magma. The unique case of the Evergreen mine I interpret as due to the accidental meeting and mingling of an ore magma and a rock (dike) magma, while both were fluid.

As to fissure systems in this belt, dikes and veins certainly follow the same fissure sets or systems. Sometimes dikes and veins coincide; but in general they are mutually independent. Different periods of dike intrusion also as a rule follow different fissures, just as the different vein periods (the pyritic type and the silver-lead type) in general follow different fissures, though all follow the same general law of trend. There is a prevailing northeasterly set of fissures, and a subordinate northwesterly set. Both dikes and veins occupy fissures of very slight displacement; and both have the "linked" habit apparently typical of fissure formation under conditions not very remote from the surface. Now, the prevalent northeast trend of the fissuring is also that of the general Colorado dike-vein belt, which traverses Central Colorado; and the northwest fissures are due to the contraction adjustment of the underlying magma mass, after intrusion.

The horizontal movement of the Georgetown vein-fissure faulting indicates lateral adjustment due to differential horizontal shrinking of the magma body beneath. According to my reasoning above, this should indicate a horizontal bulge or irregularity in the belt; and this supposition corresponds with the actual conditions. It is a case of horizontal adjustment fault-fissuring. In proportion as the vertical element of consolidating magma adjustment enters as a factor, the relative importance of the horizontal and vertical movements determines the angle of fault movement in each case, which results near Idaho Springs in dips of 60° from the horizontal. The dip of the veins in this district follows the rule for fissure veins, being predominantly at angles of 60 and 70°, regardless of strike or the direction of fault movement on the fissure plane. This indicates probably that

the origin of these fissures is in a vertically exerted force, regardless of the direction in which subsequent differential adjustments were made along these planes.

The trend of vein fissures of slight or no displacement, then, coincides in general with the long axis of the immediately underlying magma intrusion; and a minor set at right angles corresponds with the short axis. The general east-west trend of veins in western North America then may indicate an easterly-westerly trend of subcrustal magma invasions, which I have already supposed (Chapter X).

Conjugated veins may dip toward each other or away from each other. The former case I assume to be due to sagging of a magma body after intrusion; the latter to the upward pressure of a still intruding magma body. The veins at Tepezala (Chapter V) illustrate the latter type (due to direct vertical intrusion-faulting). At Grass Valley, Lindgren has shown vein systems of both types, which I explain as due to both types of pressure—up and down—exerted at different periods.

Finally, I describe the Golden Star vein, in Yuma County, Arizona, as occupying a fault fissure of earlier origin than the particular magma intrusion with which it is most closely associated in point of contiguity and age; and it, therefore, falls into my classification of immigrant veins. Previous to the ore deposition, the growth of the fault was chiefly due to sagging after an earlier intrusion, and was chiefly vertical along the fault plane. But a marked movement succeeding the ore deposition was horizontal along the same fault plane and was, therefore, a movement resulting from horizontal adjustments due to the consolidation of the magma of the later intrusion, which immediately preceded the ore deposition.

CHAPTER XVII

The Influence on Veins of Rock Texture and Rock Structure

FISSURING IN ROCKS IS MODIFIED by the character of the rocks. Firm, rigid, and homogeneous rocks develop the best fissures: igneous rocks in general are of this type. A fissure in passing from a rigid rock to a more plastic one may be deflected, break up, or even disappear. In a series of alternating rigid and fissile or shaly beds, a cross-cutting fissure may be deflected along each shaly bed, only to right itself and pursue its original course through the next rigid bed, and so on, producing a step-shaped vein, as at the Pony Express, at Ouray. In general, it is unfavorable for the strength of a vein to pass into shales.

The occurrence of lenticular veins in schist is believed to be characteristic of formation at great depths: the veins are believed to be intrusive veindikes, and the walls to have pressed inward on the veindikes, as they consolidated, and as they lost their gaseous-tension pressure, thereby tending to push the veindike into lenses. This explanation applies to both quartz and sulphide lenses in schist. In many of these cases the common explanation that vein and walls have been deformed together by a general pressure is disproved by the facts. This lenticular form is often characteristic not only of ordinary veins or veindikes but also of pegmatites, and even of alaskite; but not commonly of igneous rocks more basic than alaskite; whence I infer a comparatively greater loss of bulk and resistant strength on consolidation for the quartz veindikes and pegmatites.

In some cases, probably under considerable load, no strong fissures have developed in rocks as a result of stress due to intrusion, but the rock has been shattered throughout; and the subsequent ore-bearing solutions permeate the rock generally, producing the great mineralized masses of rock known as disseminated deposits. Those of copper and gold are most common. The disseminated copper deposit at Ray, Arizona, is cited as an example. This solution was plainly an aqueous or "pegmatitic" one, which is theoretically consistent with its derivation from the siliceous magma indicated by the granite porphyry intrusion with which it is genetically connected (Chapter XIII).

The influence of relatively impervious strata or other rock bodies on ore deposition is of the utmost importance. Since a cross-cutting fissure will almost or quite close, on passing upward from a rigid to a soft rock like shale or decomposed porphyry, the soft layer acts as a dam or blanket, and under their own pressure from below the ore solutions mushroom out below the impervious contact. Leadville affords excellent examples.

CHAPTER XVIII

The Succession of the Earthy-Mineral Veins

IN TYPICAL MAGMATIC VEIN SEQUENCES, the earthy minerals, such as quartz and calcite, not only form more or less contemporaneous gangue with the sulphide stages, but persist longer, and form by themselves barren fissure veins, which have a distinct rough sequence. At Velardeña, in Mexico, the post-metallic vein sequence in the Terneras vein was: 1, mixed earthy carbonates (of iron, magnesium, manganese, and lime); 2, calcite. In the Caldas vein the earthy-vein phases followed a first stage of arsenopyrite, and consisted of mixed carbonates containing intercrystallized realgar, probably derived from the earlier arsenopyrite.

I discussed the occurrence of arsenopyrite versus realgar in Chapter IX and came to the conclusion that arsenopyrite was essentially the form of arsenic sulphide (iron sulpharsenide) characteristic of the ore magmas; and realgar of the residual magmatic waters. I pointed out that differences in temperature alone could not account for the different form of sulphide. If, now, ore magmas are in a state of gaseous tension (Chapters XI and XII), it will perhaps be this state that determines arsenopyrite.

Many of these barren-gangue veins are homogeneous and without banded structure, and some of them contain unsupported angular fragments of wall rock; and some that are banded show that type of rhythmic banding which has been held to indicate deposition from a standing solution filling and distending a fissure. There is, therefore, no escaping the conclusion that, in some of these cases at least, the earthy-gangue solution was viscous, or in the form of a jelly. Therefore, we must believe that the first liquid residues from the gaseous-aqueous ore magmas are, often at least, gels or jellies of silica, the mixed earthy carbonates, etc., which act as intrusives, forcing open fissures.

At Matehuala, in Mexico, the last magmatic stage was calcite, preceded by barren quartz. At the Silver Lake mine, in Silverton, Colorado, after the sulphide ore sequence came: 1, mixed carbonates; 2, quartz; 3, calcite. At the Aspen mine, in Silverton: 1, quartz; 2, calcite and fluorite. At Inde, in Durango, Mexico, after the sulphide sequence came: 1, mixed carbonates; 2, barite; 3, calcite. Considering all these together, the essential common characteristic is found to be that, of the carbonates, those of manganese, iron, and magnesium represent an earlier stage, and that calcite, alone, represents a later and the last magmatic stage. Quartz has no fixed position; nor fluorite. The bases of these mixed carbonates are among the commonest ones of basic magmas, and of the earth's crust in general. But chemical affinity, as well as relative abundance, has brought about this association of elements: the bases of the carbonates in question all fall in group 2 of the periodic classification of the elements. Iron, which appears in this barren-gangue stage as a carbonate, appears in the preceding ore stage as a sulphide; still earlier is the oxide-silicate stage, in which it appears in igneous rocks and immediately-derived ores. This succession from igneous rocks to earthy-gangue veins is, of course, accompanied by a falling temperature. In volcanic fumaroles, also, the hottest stage (over 500° C.) contains no sulphur or carbon dioxide; later stages are characterized by sulphur, and still later stages by carbon dioxide. This corresponds with the noted sulphide-carbonate sequence for magmatic veins, and with the evidence that the sulphide veins are deposited at an intermediate temperature.

These divisions of veins are, however, relative, and not clear-cut, for carbonates, quartz, and sulphides frequently occur mixed and contemporaneous in all proportions.

Iron, therefore, is a metallic barometer-thermometer, since its combinations—oxides, sulphides, carbonate—indicate successive stages and a falling temperature. Arsenic constitutes a barometer-thermometer, sulpharsenide of iron occurring in the ore magmas, and sulphide of arsenic in the ore-magma residues, including the barren gangues and the residues from these. Antimony has perhaps much the same barometer-thermometer value as arsenic, the sulphantimonides being apparently characteristic of the ore magmas, and the sulphide being characteristic of the residual gangues and the waters residual from them.

The sequence of barren gangues very close to the surface is shown at Oaxaca, in Mexico. After the ore (silver-quartz) come: 1, white quartz; 2, mixed carbonates; 3, dark cherty quartz.

At the Peñoles mine, in Durango, Mexico, a thick Cretaceous limestone-shale series has been intruded by a neck of diorite, which shows some internal differentiation, and alteration to lime silicates, but no ore. The ores occur in a definite belt of fissure veins. The first ore occurred distinctly later than the lime-silicate period, and consists of pyrite, arsenopyrite, argentiferous galena, blende, and quartz. Very long erosion during millions of years elapsed before, after a reopening of the old fault-vein fissure, rich silver-quartz veins were injected. Then came volcanic outbursts; then renewed faulting along the old fissures; then barren-gangue veins were infilled. Here, then, we have a compound vein made up in three periods, of which two were widely separated. The barren-gangue veins show two chief types: an earlier white quartz, and a later calcite and earthy carbonate type. Subsequent to all vein formation was renewed faulting, which has not been cemented by vein material.

These veins in their various stages are mainly intrusive veindikes. To illustrate, a section in one locality shows: 1, a vein of silicified shale; 2, a fissure vein of white quartz, inclosing isolated fragments of No. 1; 3, translucent quartz, with inclusions of No. 1; 4, wide calcite vein, with isolated inclusions of No. 1 and No. 2. At all the stages, 2, 3, and 4, the ore solution was capable, apparently, of holding in suspension heavier included blocks. The conclusion is that the vein fluid, up till the last calcite stage, was stiff and viscous. Moreover, hardening of the jelly must have swiftly followed intrusion. These gels exuded some water on consolidation, which produced silicification in the wall rocks.

Silver sulphantimonides (stephanite, argentiferous tetrahedrite, etc.) have been to a slight degree leached from the silver-quartz ore and redeposited as a different sulphantimonide—pyrargyrite (ruby silver)—

in the subsequent barren quartz. This is not true of the copper in the original tetrahedrite, which is not thus leached. Stibnite also occurs in this later barren quartz, but does not occur in the primary ore veins: it is probably derived from the sulphantimonides in these veins. Realgar and stibnite have already been recognized as characteristic of the post-ore-magma stages; the association of secondary ruby silver with them in this case probably indicates only a local and not a characteristic association.

At Ojuela, thirty miles from Peñoles, the veins are simple, not compound; and we may examine an extensive vertical section: the ore zone is 3,500 feet deep, and passes from the chalcopyrite-arsenopyrite zone in depth upward through the blende and galena zone, to the silver zone. Above this elevation the veins are barren, though they are exposed for 2,500 feet higher. They are siderite and calcite, and rarely quartz. But many of these veins do carry stibnite, thus confirming earlier conclusions that this antimony sulphide is residual from the sulphide ore magma, and crystallizes in the earthy-gangue vein zone, and probably in the waters residual therefrom.

Reviewing this chapter, I think I have now detected the bottom of the zone of hot-spring waters, and the top of the ore-magma zones. The barren earthy gangues, up to the usually final calcite veins, are evidently still ore magmas: but from their crystallization there was a watery residue perhaps not dissimilar from certain hot-spring waters. Apparently any type of magma, from aqueous rock magma to the final calcite vein magma, gives off such aqueous residues on consolidation; and those hot waters which are residual from ore magmas may deposit realgar, stibnite, cinnabar, and gold. Fumaroles represent the same residues.

These residual waters are eliminated in the zone of refrigeration. This zone migrates downward with time. Below this zone comes the zone of differentiation; and below this the zone of no differentiation, but static conditions. The phenomena of ore deposition, with relation to the first magma-adjustment fissures, indicate that differentiation is a geologically relatively swift process, frequently completed during the early part of the period of downward refrigeration of the magma column. The differentiation of an original intermediate magma into different igneous rock types and into ore magmas goes on at one and the same time. Ore magmas are deposited only in hot rocks, which is another reason why they do not occur typically cementing considerable fault fissures, which represent long adjustment and consequently cooled rocks. Dikes are limited in much the same way by rock temperature. Hence the close association of dikes and veins; but the temperature of veindike consolidation is lower than that of dike consolidation, which

explains the fact that normally a vein follows a dike, and not the reverse.

The cessation of ore deposition with a single cycle of vein sequence at each magma-intrusion episode, or a vein sequence whose time period is very limited, also shows that though the refrigeration zone works continually lower subsequent to the intrusion, the differentiation zone does not, or at least only to a limited extent; if it did, we would have a more persistently renewed crop of veins. Therefore, the bottom of the zone of differentiation remains fixed, although the top may be somewhat lowered during the differentiation stage; and the rock once involved, at the top of the differentiation zone, in differentiation, may be reached by the zone of refrigeration, and even eventually revealed by erosion.

We may assume that, at a certain depth, balance of gaseous-tension pressure and gravity pressure prevents both magmatic differentiation and magmatic surgence. Long-continued erosion may tip the balance in favor of the gaseous-tension pressure, till a new cycle of intrusion, rock and ore differentiation, and ore deposition takes place. It follows that erosion can never reach the bottom of the zone of differentiation.

CHAPTER XIX

The Sand or Breccia Dike

THE SAND OR BRECCIA DIKE is interpreted as an unusual magmatic vein or veindike stage.

In the Pony Express mine, at Ouray, Colorado, we have the inverted order of magmatic vein sequence: 1, high-grade silver ores; 2, blende and galena. Between these two magmatic phases the vein fissure was split open and filled with an upwelling mass of mud. Some parts of the mud dike are sparsely impregnated with sulphides, and other parts have been pierced with veinlets of ore like that which immediately antedated its intrusion. The dike contains angular fragments of shale; vein quartz, etc. It is an injection breccia, and not a fault breccia, for, from the main mass, branches or sheets go off along the bedding planes of the intruded strata. Considered as a possible ore, this breccia dike is barren. The included shale slabs are arranged parallel with the (sandstone) walls, showing the incrushing pressure of these walls. In parts of this intrusive breccia, it contains pebbles rounded by attrition. The dike material is shown to have been fluid; and it is indicated that the fluid which carried all this broken rock in suspension was aqueous, siliceous, and with a little sulphide content, but sharply distinguishable from the preceding silver-barite solutions, which themselves were evidently injected as a veindike. I correlate the aqueous solutions of the breccia dike with the highly heated siliceous waters residual from the

consolidation of the silver-barite ore magma. Ordinarily, such residual waters escape along fissures, and form hot springs at the surface; but these fissures were cut off by soft, yielding strata above. Ordinarily, with the escape of water and gases, the walls of the distended fissure would have come together again; but in this case the great burden of inclusions remained as a solid "breccia dike."

In the Georgetown district, Colorado, the Mendota vein is a blende-galena fissure vein (Chapter II). Locally this sulphide vein has been split open, and a crushed granite, now cemented hard by silica, injected; this crushed granite incloses angular fragments of the sulphide vein. This injection was in pipe-like form, and the carrying fluid was evidently siliceous water and gases. Also in the Kirtley mine, at Georgetown, is a fissure vein consisting of finely crushed granite and gneiss, and this is cemented not only by silica but by barite, showing that the aqueous carrying material was allied to the vein phenomena, and again I postulate these hot waters as residual from the galena-blende magma.

At Idaho Springs, near Georgetown, are "conglomerates" occupying fissures of slight faulting. Take the Stanley mine; in the Stanley fissure, the following successive events occurred: 1, bostonite porphyry; 2, sulphides (gold-silver bearing) and quartz; 3, latite dike; 4, "conglomerate" along fissure. The rounded fragments in the conglomerate were due to rubbing against one another, and the fragments are cemented hard by silica, as in the cases previously described; and the conglomerate is similarly believed to have been an intrusion from below.

CHAPTER XX

The Origin of Certain Ore Chimneys

IN HABIT, mineral veins have much in common with igneous dikes—and differ significantly. Both occur in the tabular vein, veindike, or dike form. But ore magmas do not form the large intrusive masses that many rock magmas do; although some of the more highly differentiated igneous rocks occur only as narrow dikes. The ore magma is similarly a highly differentiated magma type; hence when we find true infilled fissure veins a hundred feet wide between walls, as we do, we do not expect much larger bodies.

Even with the conception of ore magmas as intrusive, I have shown that, like rock magmas, they avail themselves of pre-existing fissures, which they force open; and similarly drive themselves along the stratification planes of bedded rocks.

Besides the above, rock magma has another form of intrusion—the

igneous pipe or volcanic neck. We get this form, with gradually increasing horizontal cross-section in depth, at all depths revealed by erosion. The intrusive force of such magma columns is probably largely the cushion or cap of gases which accumulates at the top of a magma dome or plug; when this reaches the surface there is the characteristic gas explosion which precedes lava outpourings. Do ore magmas intrude in this form also?

In Custer County, Colorado, the Bassick mine is in an "agglomerate" neck 3,000 by 4,000 feet in horizontal dimensions, which appears to have resulted from a gas explosion; ore injection immediately followed, and then a basalt dike. The Bull-Domingo mine is in a pipe of boulders 50 by 100 feet in diameter; the formation of the pipe was followed by ore deposition. Does not this indicate an upworking ore magma, preceded by a gaseous cushion or cap?

In Gilpin County, Colorado, Bastin and Hill have described "The Patch," a fractured, brecciated and in part rounded-boulder filled pipe having a horizontal area about 400 by 750 feet. After the formation of this pipe, two types of ore deposition successively occupied the channel thus formed. The authors find that to a considerable extent the sulphides were deposited in open spaces, cementing the breccia. The sulphides were, to my mind, plainly intrusive, like the near-by fissure veins of Silver Plume, described in Chapter II. And the shape and physical characteristics of "The Patch" indicate an origin analogous to the chimneys of the Bassick and Bull-Domingo—a blow-out of gaseous accumulations, followed by the ore magmas.

The "friction conglomerate" or "breccia lodes" which I have described in this region (as in the Stanley mine) are similar to "The Patch" as to material, and indicate a similar origin, but at a later date.

The sequence of events in this region was: 1, slight fault-fissuring; 2, first dike intrusion (monzonite and bostonite); 3, slight fault-fissuring; 4, first gaseous intrusion and eruption, creating "The Patch" chimney; 5, first (pyritic-gold) sulphide invasion; 6, second (galena-blende) sulphide invasion; 7, second (minor) dike intrusion (latite, etc.); 8, second gaseous intrusion, creating "conglomerate" or "breccia" lodes along fissures (Stanley).

The Alice mine, some miles from "The Patch," is apparently in a chimney about 300 feet in diameter, which chimney is marked only by minute fracturing and not by brecciation, or "conglomerate" ("agglomerate") filling. Nevertheless, the fracturing was followed by ore deposition, in this case evidently from the aqueous type of ore magma, which I have elsewhere called pegmatitic. And it is evident, as Bastin and Hill observe, that the origin of the Alice chimney is due to a force similar to that which has created "The Patch."

The Jessie orebody, at Breckenridge, Colorado, many miles away on

this same general Colorado ore belt, is like the Alice and has a horizontal cross-section 600 by 900 feet; and here also, after the fracturing, ore deposition occurred. I regard the Alice and Jessie shattering as weaker exhibits of the results of gaseous outbreak, preceding the advent of the ore magmas; and that "The Patch," the Bassick and Bull-Domingo are the result of more violent activity of the same force.

THE ORE MAGMAS

CHAPTER I

The Origin of Ore Magmas or Solutions: Veindikes

This chapter treats of the origin of pegmatites and quartz veins by magmatic differentiation from granitic-alaskitic magmas. Some of these pegmatites and quartz veins contain sufficient metallic minerals, such as those of tin, tungsten, and molybdenum, to form ore; and some of the quartz veins contain sufficient gold to form ore.

IN MY STUDENT DAYS at college, it struck me that the characteristic association of quartz with gold and other metallic ores was an inexplicable thing: and it occurred to me that if one should find out the reason for this association he would have gone far to solve the riddle of the origin of these ores. There is no chemical affinity between gold and silica which would explain their characteristic presence in the same solution on account of similar tendencies toward solution and deposition, as in the case of the close mutual association, for example, of iron and manganese. On the assumption that mineral veins are leached out of rocks and deposited in fissures, we should hardly expect a quartz gangue, save in exceptional cases—rather a calcite gangue, perhaps, save in exceptional cases. The leaching of the granite at Silver Plume, Colorado, by ground waters, is producing abundant deposits of lime, iron, and manganese, in certain relatively deep tunnels,[1] with no silica, at least so far as casual observation goes.

Any explanation of ore deposition must explain the close association, in veins, of quartz and gold (and other metals) to be even an acceptable working hypothesis.

A few years after this problem presented itself to my mind, in 1896, while traveling through the Yukon gold district in Alaska for the United States Geological Survey, I made some observations which filled me with enthusiasm,

[1]SPURR and GARREY: *Professional Paper* 63, U. S. Geol. Surv., p. 139.

as they seemed to answer the riddle of the association of gold and quartz, on which my work hitherto had not enlightened me. To put it briefly, I found in various localities throughout the Yukon gold placer district that quartz veins could be traced gradually, even in the case of a single vein, into pegmatites and aplites consisting of quartz and feldspar. Quartz veins of this same type were here and there shown to carry free gold. The quartz-feldspar or alaskite[2] dikes (which were in part aplitic or pegmatitic) formed part of a complex series of dikes strikingly displayed on the walls of Forty-Mile Canyon, and these dikes showed a wonderful range of composition, from dikes of hornblende rock, or hornblendite, to the alaskite dikes and quartz veins. Between these two extremes a fairly complete transition was observed, each stage being represented by a different dike. Nearly all of these dikes were found to consist of the essential minerals quartz, feldspar, and hornblende, with subordinate biotite. When these minerals are present in about equal proportions, the rock is a hornblende granite or diorite, and indeed this is quantitatively the most important type, forming immense intrusive bodies, often several miles wide. From this intermediate phase variations are produced by the increasing abundance of the dark-colored minerals (hornblende with some pyroxene and biotite) to the exclusion of the light-colored ones (quartz and feldspar), or the reverse; so that by easy stages one extreme is reached in a rock consisting entirely of hornblende and the other dark minerals, with considerable quantities of metallic minerals (pyrite, pyrrhotite, ilmenite, and magnetite), and the other extreme in the quartz-feldspar rocks without dark minerals, which rocks grade into quartz veins.

The evident interrelationship as regards composition of this series of dike rocks (which are all of approximately the

[2]Feeling the need of a separate name for the important group of quartz-alkali-feldspar rocks, I later (*American Geologist*, Vol. XXV, April, 1900, p. 230) proposed the name *alaskite* for this group, which name has come into general use.

same age) suggests a common origin, and I adopted the current hypothesis that the different types had originated from a common original magma by the process called, for the sake of convenience, *magmatic differentiation.*[3]

It would be out of place for me to discuss here the evidences of magmatic differentiation or the hypotheses which have been set up to account for it. Suffice it to say that the seasoned field geologist knows it to be a fact that igneous magmas segregate (under favorable conditions, before consolidation) into unlike portions, which crystallize into rocks differing considerably in mineralogical and chemical composition—for the evidence of this segregation on a small scale is written plain on the face of many an outcrop, so that even he who runs may read; and there are very weighty arguments which demonstrate with a considerable degree of probability that in many cases interrelated dike rocks such as I have described as existing in the Forty-Mile district have originated by a similar process of segregation, on a larger scale and before intrusion. As to the processes of magmatic differentiation, this discussion may be deferred for later consideration; but as to the facts, it appears to me that we have passed out of the domain of the working hypothesis to that of the accepted hypothesis. However, one feature of magmatic segregation which it appears almost certain is of some importance in the process may be mentioned—the fractional crystallization of a consolidating magma. When a magma cools, certain minerals in some cases crystallize out first, and a relative concentration of crystallized minerals and the still mobile magma seems to take place, the fluid being drawn off in greater or less degree. Concerning what I believe to be a much more important factor, I shall have something to say in a later chapter.

Applying this current theory of magmatic differentiation, then, to the Forty-Mile dikes, I assumed an original under-

[3]J. E. Spurr: "Geology of the Yukon Gold District," *Eighteenth Ann. Rep.*, U. S. Geol. Surv., pp. 297-313.

lying magma somewhat similar to that which crystallized as the large masses of hornblende syenite or hornblende diorite, which magma had by differentiation split up into the basic dikes (of predominantly or exclusively dark-colored minerals) and into the "acid" (alaskite) dikes; and as the transition by a plainly manifest differentiation process from the alaskites to the quartz veins was unmistakably written on the outcrops, it followed that the quartz veins, in as full and unequivocal a sense as the hornblendites or the alaskites, were the result of differentiation from this assumed original mother magma. And the discovery of free gold in certain quartz veins of this type showed to me that not only the quartz veins but the gold-bearing quartz veins were the result of magmatic differentiation; and, finally, the association of gold and quartz in quartz veins became clear to me for the first time. It became evident that the feature of these veins indicative of their lineage was not the gold but the quartz, which represents the quartz of igneous magmas, which is found more or less abundantly in many igneous rocks; which, scanty or lacking in the more basic ones, such as diabase and diorite, becomes an essential feature of the granites, one of the two essential minerals of the alaskites and the sole essential mineral of these quartz veins. The gold in these quartz veins, apparently contemporaneous with the quartz, had evidently a similar origin—had been segregated or set apart, together with the quartz, from the magma during the process of differentiation.

The source of this gold, once the above relation was established, is no more mysterious than the origin of the silica. Gold is widely, practically universally, distributed in nature—in all rocks, igneous or otherwise, and even in sea water and in plants[4]; thus its presence in the original magma is a safe assumption, and its appearance in larger quantities in certain of the quartz veins in question is a matter of relative concentration in the siliceous residue.

[4] F. W. Clarke: Bulletin 616, U. S. Geol. Surv., p. 641.

That this is true is shown by the fact that some of the quartz veins under consideration carry gold, though others are practically barren.

The origin above outlined makes it clear, as I have repeatedly pointed out, that there is no hard and fast line between the magmatic solutions which deposited the alaskites and those which deposited the quartz veins, just as there is none between the alaskite dikes and the granite dikes; and that the deep-rooted preconception in the minds of many geologists as to a fundamental difference in nature and origin between these quartz veins and these dikes is unjustifiable and is a prejudice inherited from an earlier period, when our knowledge was less. This misconception is even expressed by a distinguished chemist, who places the theory of the origin of the auriferous quartz veins from solutions as opposed to the theory of these veins being true magmatic segregations, though on another page he states that a molten rock is a solution, in which one or more minerals are dissolved in another, or are mutually dissolved.[5] My explanation for the origin of the veins in question is that they are truly magmatic and that they are deposited from solutions which originate by magmatic segregation.

The existence of water as an essential component of igneous magmas has been long recognized, as well as the existence of other mobile materials which, like water, are represented sparingly or not at all in the solidified igneous rock—for example, chlorine, fluorine, boron, etc. Experiments in fusing igneous rocks and attempting to recrystallize them, and experiments as to the relative temperatures of solidification of the principal rock-forming minerals, showed long ago that an igneous rock is not analogous to a furnace slag, and that it cannot be conceived as having been fluid from sheer heat and as having crystallized from mere refrigeration.

The relative order of crystallization of the different rock-forming minerals is by no means the order of their relative

[5] Bulletin 616, U. S. Geol. Surv., 3d Ed., 1916, pp. 298, 643.

fusibility; and many igneous rocks, such as the granites, may be easily melted, but will not recrystallize on cooling from this melt. The fact that the rock magma is to be conceived of as a solution or a mixture of solutions rather than a melt has been therefore universally recognized, and the existence, in the fluid magma, of materials potent in assisting solution is indicated by the water which is found in microscopic cavities inclosed in the crystalline quartz of granite, and in the fluorine, boron, phosphorus, etc., which enter, even though slightly, into the composition of such common igneous rock-forming minerals as mica, tourmaline, and apatite. Indeed, experiments with the chief minerals of granite, as to temperatures and other conditions of consolidation, indicate that this rock crystallizes at a relatively low temperature—lower than that of the less siliceous igneous rocks, such as basalt and diabase, in contrast to the known differences of fusibility of melts; and therefore that in igneous rocks, although temperature is important as affecting solution, the magma is fluid more on account of solution than of heat. It has been commonly assumed, and with great reason, that the water and other mobile elements which have evidently played a great part in this solution mainly escape or are expelled when the solution crystallizes.

The existence of water in magmas is further shown by the vast clouds of water vapors and other vapors which arise from cooling lava when volcanic eruptions take place. This phenomenon is a striking one, and has been long known and recognized; but a few years ago a Swiss chemist caused much surprise by stating that he had collected and analyzed these emanations, and that there was no water in them; and he triumphantly announced that the theory that there was water in igneous magmas was permanently disproved. Fortunately, a more careful and capable observer, Dr. Arthur P. Day, set himself to collect the emanations from the Hawaiian volcanoes, and found that they actually contained water in abundance.

It is a matter of common field observation that granites

and alaskites grade off into a rock which may contain all of the minerals of the granite or alaskite, but with a vastly larger size of crystals, and therefore called giant granite (in allusion to the size of the crystals), or, more commonly, pegmatite (in vague allusion to the intergrowth of quartz and feldspar). Sometimes this giant granite occurs as nests in the granite, with no sharp line of demarcation between it and the finer-grained rock, and contains the same minerals as the granite; and thus the fact is clearly shown that the pegmatite magma is a variation or residuum of the granite magma. But there is more to be learned. Although the pegmatite nests (which may increase in size to considerable bodies) may show the fairly regular presence of the chief granitic minerals, intercrystallized, yet there is usually to be noted, at least locally, a tendency of these minerals to segregate, so that portions of the same pegmatite body may show feldspar massed, and other portions massed quartz. This clearly tells the same tale as the giant size of the crystals: that the pegmatite magma is far more fluid and mobile (probably because containing more water and other mobile solvents) than the granite magma, so that migration during crystallization is vastly more free, and like materials may more easily segregate.

The pegmatite magmas not only occur in nests in granite as described, but on an important scale have separated from the granite magma; and, forcing open cracks in the granite or other rocks, have formed dikes of varying size, but always very insignificant in dimensions as compared with the size of the granitic intrusions with which they are associated.

The pegmatites differ also from the granites in that they contain, locally segregated, a larger variety and amount of rare minerals than does granite. All the granitic minerals may be found in pegmatites and all locally much concentrated; and, in addition, the minerals which are rare or practically non-existent in granite. On this account pegmatites are often mined for the particular mineral or min-

erals which they locally contain in concentrated or segregated (differentiated) form, such as feldspar, mica, tourmaline, apatite, topaz, and beryl.

Granite and other igneous rocks contain various metals and metallic minerals. All of the metallic minerals probably occur in igneous rocks. Some—like aluminum and iron—make up a large proportion of the composition of such rocks. Even the relatively rarer metals have a very wide distribution. The research of chemists makes it reasonable to believe, for example, that gold and copper are universally distributed in igneous rocks, though not evenly, to be sure; and the same is probably true of many more of the relatively rarer metals. In what form these small quantities of metals occur is not always certain—largely, perhaps, as silicates, in association with the silicates of elements like iron and magnesium (such as hornblende, mica, and pyroxene).

Oxides and sulphides of the metallic minerals also occur in the igneous rocks, and interest us because it is in these forms that they most commonly occur in those concentrations which we term *ores*. Among rock-forming minerals are magnetite, hematite, and ilmenite (oxides of iron), and pyrrhotite and pyrite (sulphides of iron); probably, also, chalcopyrite, in association with pyrite (forming what was formerly called and may still be called for convenience, cupriferous pyrite—although the students of metallic ores by reflected light have shown us that cupriferous pyrite is really an intimate mixture of pyrite and chalcopyrite); also perhaps molybdenite.

In pegmatites these minerals are also present. A pegmatite in Clear Creek County, Colorado,[6] associated with a granite in which magnetite occurs as an accessory, contains so much magnetite that it is almost an iron ore. Pyrite and chalcopyrite in pegmatites are often found. Molybdenite is a frequent pegmatitic mineral, and is often so

[6] Spurr, Garrey and Ball: "Geology of the Georgetown Quadrangle," *Professional Paper* 63, U. S. Geol. Surv., p. 60.

abundant as to form at least a potential ore. I have seen it thus, entirely contemporaneous and intercrystallized with the quartz and feldspar of pegmatite, in Colorado near Breckenridge, and in the Herb Lake district of Northern Manitoba. The latter pegmatite also contains auriferous pyrite as well, and assays around $2 (average) gold to the ton, as shown by my examination to determine whether or not the pegmatite could be mined profitably.

I have spoken of the concentration (by segregation or differentiation, due to free mobility or migration during crystallization of the magma) of feldspar in pegmatites; also of mica and of many rarer minerals. I wish to take up separately and pointedly the concentration of the third of the three most important granitic minerals (feldspar, mica, and quartz)—namely, quartz. In most pegmatite bodies the quartz has locally concentrated into masses. Often a pegmatite dike may be seen in which the feldspar is confined to the edges, the centre pure quartz (or sometimes the reverse); and dikes are often found where at one point it is mainly feldspar all across the dike, and at another, close by, it is pure quartz, all across, with a gradation between, showing the pegmatitic origin of the quartz. Such dikes are commonly intimately associated with other dikes which are nearly all quartz, with only the feldspar as an accessory; and these with others where the feldspar is lacking, so that the dike is of quartz alone. In all these dikes, pegmatite, quartz (feldspar), and quartz, the quartz is of a characteristic easily recognized type—coarsely crystalline, blue-white. It is identical in appearance with the quartz of the deeper-seated gold-quartz veins, as those of the Appalachians and California; but is distinct from the quartz of the more shallow-seated gold- (and silver-) quartz veins, which I will discuss later.

I have referred above to the quartz dikes of close pegmatitic affiliation and origin. I have called them dikes because their mode of origin and manner of intrusion—of which, again, I shall speak more at length later—are identical with

the pegmatitic dikes with which they are associated. Ordinarily, of course, the quartz body is called a vein; the pegmatite, a dike. I have repeatedly called attention to the mental confusion produced by this nomenclature, which has interfered with our conception of the nature of so-called igneous rocks as well as of the nature of mineral veins and ore deposits; and have suggested that it might be better to use a single term—say, "vein"—for both "dike" and "vein." "Veins" of granite and diorite were often described by the earlier English geologists. At present I think this suggestion possibly too radical: for there are wide intrusions of igneous rocks—say half a mile wide—which are called "dikes"; on the other hand, there are deposits, along fissures and fractures, of scanty minerals from circulating waters—let us say of calcite from superficial ground waters—which we call veins; and it is good to preserve a distinction between these extremes. On the borderland between the extremes come the pegmatites, the pegmatitic quartz veins, and certain mineral-bearing veins which will be described later. These are intrusive, like dikes, but the magma from which they formed was unlike the typical magma of igneous dikes, and approached the solutions from which veins are deposited. I propose to call these, therefore, "veindikes."

Scheerer and Lehmann deserve to be especially remembered as the prophets to whom is due the main credit for understanding (from field observation principally) the nature of granitic magmas; their nature as solutions and their dependence as solutions upon contained water; and the nature and origin of granitic pegmatites. Scheerer's views were published in 1846-47, but his investigation had been going on for years before that. He pointed out that a granite magma cannot be regarded as having been in a state of purely igneous fluidity; and roughly conjectured the amount of water contained at from 5 to 20 per cent. He concluded that pegmatites were due to a "juice" which exuded from the granites, and which could hardly be anything else than water containing silica and other

solid substances in solution. He also suggested that this juice penetrated into the stratified rocks with which the granite came in contact and took a large part in contact metamorphism.

Scheerer's valuable and thoughtful conclusions were practically forgotten for several decades, till in 1884 Lehmann published the results of his studies of the pegmatites of Saxony, affirming Scheerer's views and offering much sapient detail and argument. He argued (against the theory of lateral secretion which had obtained just previously) that the pegmatite dikes were injections and that their mode of origin was at least analogous to that of granite dikes, and noted the transition from pegmatite dikes to quartz dikes, which must therefore have had a closely similar origin. When Lehmann's work was published, it was, I understand, received with ridicule by the geologists of the day, and his opinions were consigned to oblivion. Nor were they apparently given their due and great consideration up to recent years, although there is little which has been done since which, in my opinion, adds to the accuracy of this general conception.

The deep-rooted belief, impression, or preconception that a "vein," such as a quartz "vein," must necessarily have an entirely distinct origin from a "dike," such as a "pegmatite dike" or a "granite dike," seems to have retarded for many years the recognition of the significance of one of the commonest and clearest of field phenomena. In Australia, to be sure, Howitt, in 1887, came to the conclusion that certain "veins and even strong dikes" of crystalline quartz or of quartz and tourmaline, which are associated with an increasingly siliceous series of granitic intrusions, "represent the last portion of the still fluid (uncrystallized) magma." In the United States, A. C. Lane, in 1894, called attention to the fact that "there is a continuous series from pegmatites to segregation veins and true fissure veins filled by ascent. . . . Pegmatites are one form of residual magmas, the segregation veins a further step"; and in 1897

Crosby and Fuller, in the most important essay on pegmatites which had up to that time appeared in American literature, maintained that the quartz veins which have such a frequent and obvious relation to pegmatite dikes are the end product of the same great process of differentiation which has produced the pegmatites.

All this my discussion of granites and pegmatites and quartz veins, dikes, or veindikes is of course for a clearer understanding of the origin of ores, and ore deposits, and of mineral veins. Though the relation of pegmatite dikes to quartz dikes or veins was, as above described, noted by many, and though some of the boldest thinkers recognized that the quartz veindikes, like the pegmatite veindikes, were of magmatic origin, and represented essentially the siliceous extreme resulting from the differentiation of igneous (usually granitic) magma, yet it is psychologically interesting to note that such was the hold, on the minds of the same observers, of the current theories as to the origin of ore deposits (by lateral secretion from wall rocks or by hot-spring action) that where they found these quartz veins containing metallic minerals, and so coming under the head of ore deposits, they straightway separated them from the magmatic quartz veins with which they were associated and with which they were otherwise identical, and assigned to them a non-magmatic origin. This was striking in the case of Howitt, in Australia, above referred to. In spite of the evidence which he set forth in regard to the magmatic origin of many of the quartz veins in the auriferous districts, and in spite of the fact that he had shown the auriferous quartz veins to be connected with intrusive granite contacts, he turned his back on these results when he attempted to explain the origin of the auriferous quartz veins, and reverted to the old theory that these veins were due to circulating waters which derived their silica and gold from the Silurian strata through which they had percolated, and that the gold was originally contained in the Silurian ocean and was precipitated in the sediments of that period.

Thus did the unfounded hypothesis of Sir Roderick Murchison prevent Mr. Howitt from seeing what he had, to all intents and purposes, already seen; and the marvelous tenacity of error is well illustrated.

I have been unable to find, indeed, that any geologist recognized that quartz veins of pegmatitic origin and metalliferous quartz veins might be not only in the same class but one and the same thing, till I published this opinion in 1898, as a result of my work in Alaska in 1896—certainly, I think, not as regards the auriferous veins, or, as they are commonly called, the gold-quartz veins.[7] But others were of course working along the same lines. The book of Nature has no limited edition, and all may read the record, flung open to the sun and skies. Only a little later than my publication, and in the same year 1898, Hussak described an auriferous quartz vein in Brazil (Minas Geraes) as intrusive, and as being an ultra-siliceous granite apophysis or dike. His interpretation has been questioned by some writers, and I have no personal knowledge of this occurrence; but it shows the current trend of investigation. Since then a great deal of literature has been contributed to the subject.

I have tried to sketch briefly the development of the idea of certain mineral-bearing quartz veins as a phase—as a product of the differentiation of so-called igneous magmas; as formed, indeed, by magmas, in a sense. In a lesser way, the conception that a granite or alaskite dike crystallizes from a magma—a pegmatite dike, let us say, from a magma, but a pegmatitic quartz vein from a solution—is almost as misleading as the too rigid use of the words dike and vein. Let us remember that a magma is a solution, and that the quartz veins of pegmatitic origin are deposited from a magma; and we may perhaps keep the conceptions clearer if we (correctly) call the granitic magma a magma solution, and the quartz magma also a magma solution.

The theory of the formation of mineral veins by emana-

[7] See, however, page 76.

tions from volcanic and other igneous rocks is, however, one which has been held by many, and dates back at least to the time of Elie de Beaumont in 1847.[8] This theory

[8] De Beaumont foreshadowed some of the most advanced recent thought with astonishing closeness, considering the divergent trends of opinion which since then have obtained and successively predominated. In a masterly treatise, he first drew together as closely connected the mineral deposits from volcanic fumaroles and those from spring waters: "The gypsum which crystallizes in the fissures of certain volcanoes is as hydrous as that deposited from certain mineral waters. In short, the sulphurous volcanic materials are products of the wet way, as much as the precipitates of warm springs are products of heat, and both classes of products are only to be separated through the outward form of occurrence, which they have at the earth's surface. Basically, they have the same origin, and, therefore, do not form two really different classes."

He stated his theory of the origin of the mineral-forming waters or water vapors as follows:

"The water vapors, which spring either from the cooling lava, or from the crater-fissures, form sometimes, through their contraction, veins of hot water, which contain different salts and are really warm springs. Like the volcanic emanations, they originate from a natural distillation and sublimation." He stated that the problem of the localization of mineral veins is quite analogous to that of mineral waters or hot springs. "In general, mineral waters are chiefly found where volcanic eruptions have taken place, or at least in places where the formations are highly altered. But this is exactly the usual occurrence of veins, which are found principally where the formations are disturbed and faulted, and eruptive rocks are near by. The principal difference is that warm springs are associated with the recent eruptives, the veins with the older ones." And only by logic can we arrive at the facts, for, as de Beaumont says, "One cannot penetrate the interior and demonstrate the connection between the fissure-channels and the mineral springs, and show the point where they can extract from the eruptive rocks their heat and their constituents."

De Beaumont's classification of veins is interesting—he divides them into two classes: those which have been formed by successive deposition on the walls of open fissures (marked by minerals like quartz, barite, calcite, fluorite, galena, etc.); and intrusive "veins" like basalt and porphyry. The former, he says, are marked by symmetrical layers, with frequently central vugs; the latter are quite filled, and show no symmetrical layers. "To the former or 'concretionary veins' belong most mineral veins: but sometimes the intrusive veins are ore-bearing." Basalt dikes may become iron ores by an increase in the proportion of contained magnetite, as at Taberg, in Sweden. Also, serpentine may carry chromite and magnetite, and become an ore. Furthermore, here and there masses of magnetite and hematite may be regarded as eruptive rocks, "as on the island of Elba." He also recognized the class of deposits which more

arose from observance of the emanations from volcanoes, and the discovery that these vapors in some cases deposit metallic minerals such as cinnabar, realgar, copper and lead chlorides, and occasionally tin and cobalt minerals, on the walls of fissures through which they emerge. The vapors from these fumaroles contain water, and have been currently supposed to be largely water—Dana thought 99 per cent, and Scrope thought 999 parts out of a thousand.[9] De Beaumont and others believed that from such direct aqueous and gaseous emanations, which contain solids in solution, and are expelled on cooling, a certain type of hot springs derive their water, and from this magmatic or "juvenile" water (as it was later termed by Suess), or from gases similarly emanated, or from both, mineral veins are formed. From emanated gases, de Beaumont believed (and the conception has not been materially changed to the present day) the tin lodes were formed.

In 1895 I advocated this volcanic emanation theory for the ores of Mercur, Utah, attributing one period of ore deposition to water separated from an intrusive porphyry sheet at the time of cooling, and a later period to mineralization by gases from a cooling body of igneous rock below.

We have taken many long strides in economic geology in the last twenty-five years, and we should congratulate ourselves that we have come to a practical agreement upon *the relation of igneous activity to ore deposition,* for the geographical connection is very evident. As for the rest, we have many observations to make, much to lay together, and much to deduce.

In summing up, as above, the development of the explanation of the origin of auriferous quartz veins by a process of magmatic differentiation from granitic magmas, and my

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recently have been called contact deposits, or contact-metamorphic deposits, and which frequently are accompanied by masses of garnet.

[9] In Hawaii, according to Shepherd, the gases contain around 60 to 70 per cent water; at Katmai, Alaska, according to Allen and Zies, over 99.9 per cent. The former are from basaltic lavas; the latter from rhyolite.

observation that, so far as I knew, I was the first to propound the theory, I must make an exception in the case of Thomas Belt, whose conclusions I encountered only in 1916, after writing the above. Thomas Belt was an English mining engineer, and a great naturalist, who, among many other activities, managed a gold mine in Nicaragua for years, and wrote in 1873 a little book called "The Naturalist in Nicaragua,"[10] which is a charming account of many things in Nicaragua. Charles Darwin and many other illustrious scientists admired this book, which among other fascinating things gives instances of protective mimicry, especially among insects. I am impressed with the idea that Thomas Belt was, or should be, among the most famous of mining engineers. He refers to an earlier work, "Mineral Veins," published in 1861, to which I have not had access. Belt writes:[11]

"Several years ago, I endeavored to show that mineral veins in granitic districts occurred in regular sequences, with certain intrusive rocks, as follows: 1st, intrusion of main mass of granite; 2d, granitic veins; 3d, elvan[12] dikes; and, lastly, mineral veins, cutting all the other intrusive rocks." (Note here that Belt appears to use the term dike and vein almost interchangeably, and that he refers to mineral veins as intrusive rocks.) Quoting further:

"In every region of intrusive plutonic rocks that has been thoroughly explored, a similar succession of events, culminating in the production of mineral veins, has been proved to have taken place, and it appears that the origin of such veins is the natural result of the plutonic intrusion. There is, also, sometimes a complete gradation from veins of perfectly crystallized granite, through others abounding in quartz at the expense of the other constituents, up to veins filled with pure quartz, as at Porth Just, near Cape Cornwall; and, again, the same vein will in some parts be filled

[10] Recently republished in "Everyman's Library."

[11] "The Naturalist in Nicaragua," p. 76.

[12] Elvan is a British term for aplitic dikes.

with feldspar; in others, contain irregular masses of quartz, apparently the excess of silica beyond what has been absorbed in the trisilicate compound of feldspar. Granitic, porphyritic, and trappean dikes also sometimes contain gold and other metals; and I think the probability is great that quartz veins have been filled in the same manner—that if dikes and veins of granite have been an igneous injection, so have those of quartz. By an igneous injection, I do not mean that the fused rock owed its fluidity to dry heat. The celebrated researches of Sorby on the microscopical fluid cavities in the quartz of granite and quartz veins have shown beyond a doubt that the vapor of water was present in comparatively large quantities when the quartz was solidifying. . . . The presence of the vapor of water would cause the liquefaction of quartz at a much lower temperature than would be possible by heat alone, unaided by water. I know that this opinion is contrary to that usually held by geologists, the theory generally accepted being that mineral veins have been produced by deposits from hot springs; but during twenty years I have been engaged in auriferous quartz-mining in various parts of the world, and nowhere have I met with lodes the phenomena of which could be explained on this hypothesis."

My observation in 1896 that the gold-quartz veins of the Yukon district in Alaska were closely related to pegmatite veins, and were, indeed, the result of magmatic differentiation (the same process which had evidently produced the whole series of dike rocks in the Forty-Mile district), was followed by work on the gold-quartz veins of the Silver Peak district, Nevada,[13] where I found proof of the same relation and the same origin.

In the Silver Peak region the rocks are mainly true granites, composed of alkali feldspar and quartz, with some biotite and muscovite. These rocks often pass into slightly later types composed entirely of alkali feldspar and quartz, and so having the composition of alaskites. The alaskite

[13] Work published in 1905 and 1906.

gradually passes, by diminution of the feldspar, into pure quartz "veins," which have very much the same chemical and genetic relation to the alaskite that the alaskite has to the granite. The typical auriferous quartz of the Mineral Ridge district is white and crystalline and is in appearance and nature like that of the gold quartz (deep-seated type) found in so many districts. It occurs in the form of overlapping lenses intrusive into metamorphosed slaty limestones along a certain zone, and associated with similar lenses of alaskite (Fig. 1). The quartz contains gold and a

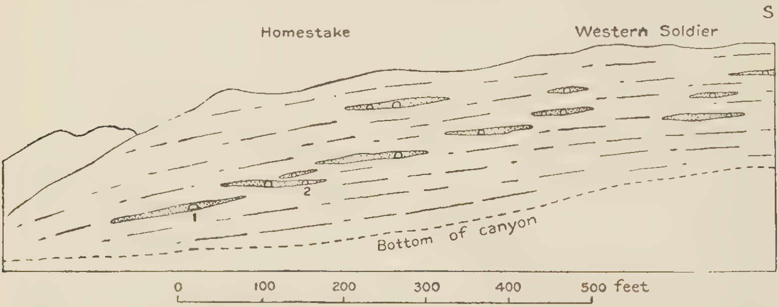

Fig. 1.—Silver Peak, Nevada. Rough sketch of east wall of canyon at Drinkwater mine, showing zone of auriferous quartz lenses. I interpret this as a slightly diagonal up-cutting auriferous quartz veindike, which before consolidation has been separated into lenses by the pressure of the wall rocks. From J. E. Spurr: Professional Paper 55, U. S. Geol. Surv.; Fig. 7.

little silver throughout, the gold being principally in a free state, though some is contained in sulphides. Typical quartz and typical alaskite form two ends of a rock series between which every gradation is abundantly represented. As a rule, the gold grows rapidly less with increased feldspar, although rarely feldspar-bearing veins carry good values.

Study of the crystallization of the alaskite shows that in it the quartz is distinctly younger than the feldspar. Many observations show that the first-formed feldspar crystals in the magma cohered to form a mass rigid enough to be partly cracked and fissured in place, and that the residual fluid solidified as quartz in these fissures, as well

as in the spaces between the feldspar crystals. Besides occurring in these forms, the quartz magma collected in larger masses and by itself formed on a small scale an independent intrusion in the same sense as the alaskite magma had done.[14]

There is a point in our advance which I wish to emphasize—namely, that not only is the association of quartz and metallic ores in a way adventitious, but the association is a misleading one, which by analogy rather leads us to expect that all quartz veins shall be metalliferous. It appears, however, that not only is this by no means the case, but the process of magmatic segregation and differentiation tends to separate the silica from the metals and deposit them separately; and this is one of the most essential laws to understand in studying ore deposits, for the illustrations of this principle which we shall find in nature are many and convincing.

As to the depth at which the pegmatitic quartz veins with their attendant ore deposits were formed, it must have been considerable. These veins, like the pegmatites, are exposed only in sections where the erosion has been enormous, as in the pre-Cambrian areas of the Eastern United States, in Eastern and Central Canada, and in other regions where vast amounts of cover have been stripped off. Certainly, the depth must amount to several miles from the surface at the time of formation—my impression is that it is many miles. None of the veins which we have to study in the relatively shallow zones are associated with pegmatites, nor is pegmatite found in connection with the veins in the great intermediate zones, where we may often establish a depth of many thousands of feet at the time of deposition.

As to temperature, let us consider what is known as to the conditions of granite crystallization. According to Brauns,[15] mica, one of the characteristic minerals of granite

[14] *Professional Paper* 55, U. S. Geol. Surv., p. 11.
[15] *Chemische Mineralogie,* pp. 247, 248.

and pegmatite, is unstable above 800° C. and passes into other silicate combinations, such as olivene, augite, and scapolite (the first two characteristic of the basic igneous rocks). Hornblende is a common granitic mineral, but augite is not, typically. Hornblende has been formed artificially in the presence of water at about 550° C.; above 500°–800° C. augite is formed instead of hornblende.[16]

Wright and Larsen have shown that quartz is unstable above 800° C., above which point it passes into tridymite: that the quartz of granites and pegmatitic granites crystallized above 575°, and that vein quartzes, including the quartz of pegmatites and pegmatitic quartz veins, crystallized below 575° C.

According to these data, the granites, including the pegmatitic granites, crystallized at temperatures from 575° C. up to a certain point, which must be well below 800° C.; and the pegmatites and pegmatitic quartz veins crystallized at from 575° C. down to a certain somewhat lower temperature.

I have set myself in these essays to record, so far as possible, my own observations and deductions, as I find that by citation one falls into errors and into a mixture of good and false observations, of correct and incorrect deductions; therefore, regarding the occurrences of metallic minerals in pegmatites, sufficient to form ores, I will say that in my experience the ore-bearing pegmatites, properly speaking, form commercially the least important class of ore deposits. I have seen molybdenite in pegmatites as an original component, in sufficient quantity to render it a potential ore; but even this ore was of low grade. On a number of occasions I have found gold by assay, and even free gold visible to the naked eye, in the quartz of pegmatites, but these ores were also low grade, and I know of no case where the gold reached the quantitative proportion (say an average of a quarter ounce to the ton of ore, or

[16] J. H. L. Vogt: "Mineralbildungen in Silikatsmelzlösungen," Christiania, 1903, pp. 6 and 7.

over) necessary at the present period to make them commercially workable ores. A recital of the cases where metallic ore-minerals have been found as primary constituents of pegmatites would be long and impressive, but would obscure the perspective. Not only gold and molybdenite but copper sulphides, iron oxides and sulphides, and other minerals so occur. Still the fact remains, that while many pegmatites are being mined, it is usually not for the metallic minerals but for the non-metallic minerals—such as mica, feldspar, etc.

Closely allied to the pegmatites, however, are the pegmatitic quartz veins, in which the segregations of metallic minerals are often considerable and are valuable commercially. These are pegmatites with practically all the non-metallic minerals withdrawn save quartz. They characteristically occur in the vicinity of true pegmatites and show by transition their intimate connection with and derivation from these. They may and often do contain feldspar and other non-metallic pegmatitic minerals, but only in small quantities and as accessory minerals. They evidently represent, in short, a more highly differentiated, more strictly residual pegmatitic magma, from which most of the principal granitic constituents save quartz have been separated.

The commonest ore deposits of this kind I have seen are those of tungsten, as at the United States Tungsten Mines, at Ely, Nevada—containing both hübnerite, or tungstate of manganese, and scheelite, or tungstate of lime. Certain molybdenite veins which I have seen have a similar origin.

Probably closely allied with these are the tin veins, where cassiterite, the oxide of tin, occurs in pegmatitic quartz veins or even in pegmatites. I am not familiar with any of these occurrences, which are found in various places in North America (as in the Black Hills of Dakota, and on the Seward Peninsula of Alaska), in Cornwall (England), and elsewhere. The tin veins were very early recognized as having a close connection with igneous (granite) intrusions,

and have been usually considered as being a type of ore deposit apart from the others, and were explained as due to gaseous or pneumatolytic after-emanations from the cooling granite. So plain is the transition from tin-bearing veins to pegmatites, and from this to granite, that these veins securely kept this explanation during the prevalence of the theories, for the origin of most other ore deposits, of lateral secretion, deposition from downward solution (ground waters) and from hot springs (regarded as heated and ascending ground waters).

The origin and mode of deposition of tin veins seems to be probably like that of the tungsten and molybdenite veins above described: veins of pegmatitic origin, derived from differentiation, like pegmatites, but representing a slight further stage in the differentiation (tin has been found in pegmatites in fair quantity, in South Carolina, for example). As to why tin should occur in one district, tungsten in another, and molybdenite in a third, it seems to me that that is a question of the relative distribution of these rarer metals in different parts of the earth—of metallographic provinces, in short (Chapter X). Tin deposits are almost invariably associated with siliceous granite and alaskite intrusives, a fact which has long been recognized; and, as far as my observation goes, the same is true of pegmatitic quartz veins containing tungsten and molybdenum.

Closely related to these metalliferous quartz veins of close pegmatitic affiliation are similar quartz veins not so closely associated with pegmatites and carrying scattered free gold, auriferous pyrite and other sulphides. Veins of this type are numerous, characteristic, and are very important commercially. They represent the typical so-called gold-quartz vein—the gold-quartz vein of California, of Canada (in large part) and the Appalachians, and, as I believe, of Australia and many other parts of the world. They consist of quartz of a very characteristic type, bluish to white, crystalline, with a general appearance and luster quite different from the quartz of the Tertiary gold-quartz

vein, so that it is ordinarily easy to identify this type at a glance, even from hand specimens. These veins usually carry only a small proportion of metallic material, which occurs as free gold, and as disseminated pyrite, with frequently disseminated galena, a little chalcopyrite, and rarely tellurides of gold. These sulphides are frequently highly auriferous. The veins carry a little silver, but as a rule the amount of this mineral is commercially unimportant. In these veins large concentrations of high-grade ore are rare or lacking, which is not the case with the shallow-seated gold-quartz veins, to be described later, as, for example, at Goldfield, in Nevada, and El Oro, in Mexico. The deep-seated veins may be very spotty as to values; or the oreshoots may be very large, and the mines may produce large amounts of medium-grade to low-grade ores. The gold is so relatively loosely locked in the quartz and sulphides that most of it can be extracted by simple amalgamation, or amalgamation and wet concentration, after coarse grinding; or, in other words, the ores are technically called free milling as contrasted with the gold (and silver) ores of the Tertiary districts above cited, where the gold (and silver) is more intimately locked up in the ore, so that the ores usually require fine grinding and cyanidation in order to secure good extraction. The first named process is much cheaper than the last named; therefore, relatively low-grade ores of the deeply formed zone can be profitably mined and milled under conditions where ores of similar grade belonging to the shallow-formed zone could not be handled at a profit. Thus, ores of the first type running $5 or less are often mined at a profit, under present conditions; while ores of the second type should ordinarily run twice as much to pay expenses. The oreshoots of the deep-seated gold-quartz veins frequently persist to considerable depths, as compared with those of the shallower zone; therefore, mining is steadier and more regular, and mining costs can be reduced to a lower figure and there maintained.

The gold-quartz veins of the deeper-seated type occur only in regions which have undergone deep erosion, and were therefore formed only at a very considerable depth. Moreover, the fact that the locus of formation of these veins is close to that of the pegmatites is shown by numerous occurrences. I have above referred to and casually described the occurrences in the Yukon district of Alaska and at Silver Peak, in Nevada. The Silver Peak veins have been made the subject of extensive mining operations (average grade $4 to $5). At Helvetia, in Arizona, where, locally, transitions may be noted between pegmatites and typical quartz veins, the veins are auriferous, and while not important enough to be made the subject of lode mining,[17] the detritus derived from the disintegration of these veins had been washed in a small way for placer gold. Similarly, the enormously rich placers of the Yukon, in Alaska (including the Klondike), were derived from the erosion of veins of the same type, none of them important enough for lode mining.

On Crowduck Bay, Herb Lake, Manitoba, Canada, I have examined and developed and sampled as a possible mine a property showing many dikes of alaskite pegmatite (connected with a great granite intrusion) in schist. Other dikes (veindikes) were of quartz with pegmatitic phases; and still others were of quartz alone. Some of the quartz and quartz-pegmatite veins (veindikes) carry contemporary molybdenite and pyrite in small amount, and assay up to several dollars in gold. In this region are many similar gold-quartz veins, identical in every respect, which show no pegmatitic transitions.

Gold-quartz veins of this type which are closely connected with pegmatite veindikes, therefore, often are thus demonstrated to be true veindikes themselves. The mechanics of their intrusion and formation are plainly identical with those of the alaskites and pegmatites which they accompany and follow. Perhaps on account of the great

[17] One of the veins assays several dollars to the ton.

depth at which they were intruded, it is very often the case that the wall rocks are schist, schist being formed from massive rocks by great pressures. In these schists the alaskite, pegmatite, and quartz veindikes have frequently a tendency to form lenses, this being a form which this type of injected material seems to tend to assume under these great pressures. Study shows that probably the magma from which such pegmatite and quartz veindikes formed was relatively fluid. On the other hand, the pressure of the liquid was sufficient to open the walls of the veindike against the enormous rock pressure. This magma pressure, which accomplishes intrusion, will be discussed later, and will be called telluric pressure.

These quartz veindikes, especially the lenticular type indicating great depth and pressure, are, as before stated, usually of low grade in respect to gold contents. They are transitional, however, in the same districts and in neighboring districts into similar gold-quartz veins, which have more the tabular form of dikes and veins, although in the same type of wall rock; and which carry typically more gold, although still usually of quite low grade. The form of these veins suggests that they were formed above the lens-shaped deposits, at a progressively less depth and pressure. Again, in many districts only the continuous or tabular veins of this type occur. Of this latter type are most of the veins of the Mother Lode region in California, and both types are illustrated in many parts of the Appalachians, and in Eastern and Central Canada.

CHAPTER II

The Mode of Injection of Mineral Veins, and the Nature of Ore Magmas or Solutions

This chapter treats of the transition from molybdenite-bearing pegmatite veindikes to veins and lenses of gold quartz, arsenopyrite, and chalcopyrite. All these are found to be in many cases intrusive and formed from highly concentrated or even pasty ore magmas. Galena-blende veins and pyrite-siderite veins are also found to have been in many cases deposited from highly concentrated or even viscous solutions. On the other hand, there is evidence of a thinner type of ore solution, sometimes perhaps residual from the highly concentrated type.

I CANNOT GO VERY FAR in the discussion of igneous rocks and mineral veins without inquiring into the question of the manner of intrusion of these rocks and of certain veins which I have previously called veindikes. The phenomena of igneous intrusion have a profound significance as regards mineral veins and ore deposits in general, in many ways which can best be developed in the course of an extended analysis.

According to the old school of economic geology, one of the main things in the study of ore deposits was to find how the "openings" in the rocks were formed—by rending or faulting, or by solution (such as produces caverns in limestone), or both. Many ingenious explanations have been offered to account for the "fissures" which formed the supposed openings which were filled by the "fissure veins." This was held to be the main problem. Given the openings, they would be filled or cemented by mineral veins, whether by lateral secretion, or leaching from the wall rock, according to one school hardly yet extinct, or by the ascending or descending or laterally moving hot or cold waters which form part of the regular ground-water system of the crust. It was supposed that the mineral precipitation from

waters circulating in these fissures and irregular openings built up gradually a vein-filling till the opening was completely cemented; and we had always in mind, therefore, the type of a "crustified" or banded vein as a natural result, although as a matter of fact we rarely succeeded in finding a good example.

Though this good old conception, natural because it appealed to the simplest explanation, may in some cases be applicable, in a minor degree, yet it has been gradually borne in on my mind, in the course of years of observation on actual veins, that this is another of the preconceptions which have stood in the way of our understanding of mineral veins. Openings do exist in the earth—irregular cavern-like openings in soluble rocks, like limestone, and smaller but more regular fissure-like openings in relatively insoluble rocks, like granites or quartzites. We know this because we encounter them underground in mining operations, down to the depth of thousands of feet; wherever, in fact, mining operations have penetrated; and water circulates along these openings, as we find out when mine workings tap them and the flood of water which they carry. "Water-courses" is the miner's name for them, and I have known places, as, for example, in the deep workings at Tonopah, where the rock would be entirely dry until one of these great water-bearing fissures was tapped. But, almost invariably, there is little sign of vein deposition or cementation along these water-bearing fissures or channels; indeed, the opposite action is usually found to be taking place—disintegration and gradual solution of the crushed rock along the fissure or fracture zone, with the attendant enlargement of the openings. This is practically the universal fact; it is especially significant, as I have pointed out,[1] in regions like the lead-zinc district at Flat River, Missouri, which is typical of the lead and zinc deposits of the Mississippi Valley. Here the almost universally accepted theory is that the vast deposits of lead and zinc sulphides have been

[1] *Econ. Geol.*, Vol. X, No. 5, p. 472.

leached from the Paleozoic sedimentary rocks, by circulating waters of atmospheric or meteoric origin (such as we now encounter in mines), and deposited along channels of circulation or water-courses. Deposition from ordinary descending waters has been perhaps the favorite theory; but in the Flat River district there was found proof, from the localization of the flat bed-like sulphide deposits (which have largely replaced bedded limestone) on the under side of impervious shale beds which had acted as blankets to the metalliferous solutions, that these solutions were ascending; so the theory was modified sufficiently to make the waters artesian and ascending, while still being derived from the surface and having leached their metallic contents from the sedimentary rocks in their journey.

When we find, as we do, in these mines, strong water-bearing fissures which we know from geologic evidence were formed at a remote period, with large amounts of water vigorously circulating along them, and discover no trace of metal or other vein deposition, we observe a striking fact opposed to the popular theory; and the more so that these waters could have drawn on for metal contents, not the postulated traces in the sedimentaries, but actual ore deposits which the fissures and the waters traverse. The case in this district is typical of what we find in the mine workings, however deep, of other mining camps. Only one apparent exception comes to my mind, the case which I have already mentioned of the Lebanon tunnel (p. 61) near Georgetown, Colorado, where circulating waters have deposited calcite in mine openings. There is no limestone in this region, however; only rocks like granite, porphyry, and gneiss, from which the circulating waters have derived their lime. The existence of such a barren calcitic deposit as this is, however, an even more striking argument against the theory of vein deposition from ordinary circulating ground waters than is the typical empty fissure; it leaves the deposition of the metalliferous veins of quartz by this theory still further in the outer realm of unsubstantiated

imaginings. It is, moreover, not fair to cite this case as an exception: for the precipitation of calcite is due to the current of air brought in from the tunnel, so that the deposit is analogous to the calcareous precipitates around the mouths of springs, rather than to vein deposition.

In short, the result of my own experience is this: I have traversed and studied exhaustively and mapped carefully, either personally or with the help of my associates and assistants, many thousands of mine workings, during a period of many years. These mine workings have been at all depths, frequently thousands of feet below the surface. At all depths I have noted openings in rocks, especially along fault or fracture zones, and found waters circulating vigorously along them. These waters were cold, lukewarm, or (rarely) hot.

In no case have I seen any vein in process of formation. To this statement exception must be made for the superficial enrichment and deposition processes whereby ores are reworked and often concentrated by superficial and descending ground waters. Of this, later. But as to primary veins and ore deposits, my own experience shows clearly the lesson that they are not formed underground under ordinary and every-day conditions, regardless of the existence of openings and circulating ground waters and the presence of disseminated metals in the rocks; these conditions have nothing to do with primary ore deposition. The primary veins are formed in portions of the crust which the miner has not tapped, either by reason of these portions being too deep or too hot; they are formed for that reason under conditions which are beyond our experience, and unlike anything we have witnessed, and it may well be that we are personally unfamiliar even with analogous processes. I think it wise to fix this fact in mind, for our efforts to visualize the formation of mineral veins and ore deposits have been by comparison with phenomena which we have seen; let us remember that the only evidence which we have is that which we can deduce from examination of the ore deposit

long after it has been formed, when we find it possible to reach it through the erosion of the crust or the driving of mine workings. We are endeavoring to fathom with our minds a strange realm, with which we have no acquaintance, and where the laws and occurrences of the surface and the superficial zone which we have visited cannot be assumed to apply.

How, then, are veins formed, if not by the gradual filling of openings, fissures, and cavities by slow precipitation from circulating waters, as has been most commonly believed and as I for years did not doubt? The problem is, as I see it, not a simple one, and it will be better not to assume that all veins are formed alike, and to proceed with our examination of the evidence decorously. I have myself experienced the setback of falling into the error of generalizing too broadly from a limited set of data, and I have marked the same error in others; and though the conclusions in these essays will necessarily be drawn mainly from my own experience, in accordance with the plan determined on, yet I shall go over many instances before inviting you to final general deductions.

Let us, therefore, take first one extreme although common type of vein formation, the irregular or lenticular bodies of more or less auriferous quartz which are associated with granitic and pegmatitic injections and which often occur in schist in the older rocks, showing formation at relatively great depths.

Concerning the carefully studied occurrences at Silver Peak (p. 77), the quartz, like the alaskite, has been deposited as a zone of lenses, having the usual peculiar overlapping arrangement of lenses of this type—an arrangement for which we must infer some physical law (Fig. 2). These quartz lenses, which vary in size up to 50 feet or more in thickness and several hundred feet in length, and the accompanying and more abundant alaskite lenses, have intruded a belt of thin-bedded shaly and calcareous Cam-

brian sediments[2] (limy shales), intercalated with limestone beds which have been changed into marble. The main zone of ore lenses lies in a belt 100 feet or more wide, which outcrops for a mile along the mountain side, and dies out in both directions (Fig. 1, p. 78). The detailed occurrence of these lenses is of extraordinary significance for this whole type of lenticular veins, and I am therefore reproducing a number of sketches which I made for my original report. The intrusions are almost invariably parallel to the bedding, which dips at angles up to about 45°; very rarely they cut across the bedding.

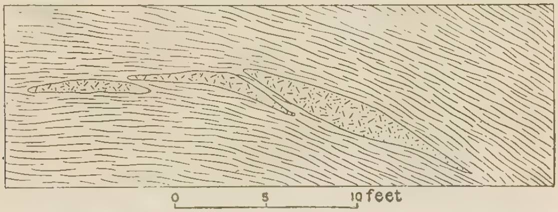

FIG. 2.—Silver Peak, Nevada. Drinkwater mine. Vertical section of alaskite-quartz string of lenses in schist. Suggests originally continuous veindike, trapped into lenses by wall pressure before consolidation. From J. E. Spurr: Professional Paper 55, U. S. Geol. Surv.; Fig. 2.

In form the quartz bodies (including those which are auriferous, and so form the ore deposits) occur, as I have just said, in lenses of various dimensions, as seen in both horizontal and vertical plan; and these lenses typically overlap or are arranged in imbricated order (Fig 3). They disappear by wedging out; frequently also by splitting into several forks, the country rock coming in between (Fig. 4). A series of stringers may unite, if followed in any direction, into several feet of solid quartz. The result is a great complexity, and no vein or lens can be counted on to continue long in any direction.

The lenticular quartz bodies have their original form in which they were deposited, and have not been produced by crushing and shearing, as I at first assumed. This is

[2] *Professional Paper* 55, U. S. Geol. Surv., 1906, p. 108.

shown by the fact that the wedging out of lenses is not accompanied by evidence of unusual movement or special shearing in the inclosing rock, but is accomplished by a fraying and splitting into many sheets, between which come

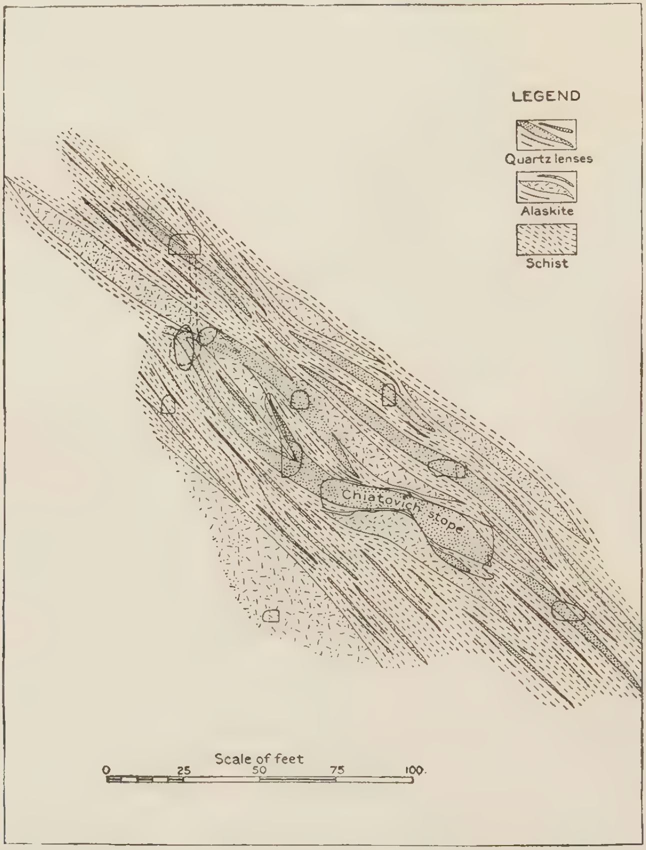

Fig. 3.—Silver Peak, Nevada. Vertical cross-section of chief stope workings, Drinkwater mine. Shows characteristic branching and lenticular form of auriferous quartz veindikes in schist. From J. E. Spurr: Professional Paper 55, U. S. Geol. Surv.; Plate XII.

in gradually thickening wedges of rock (schist). Also, the reuniting of sheets after splitting (as seen for example in Fig. 3, which is a carefully made mine section) shows conclusively that the form is not due to movement. More-

over, the alaskite and quartz intrusions are not schistose, although the wall rock is. The laminæ of the schist are

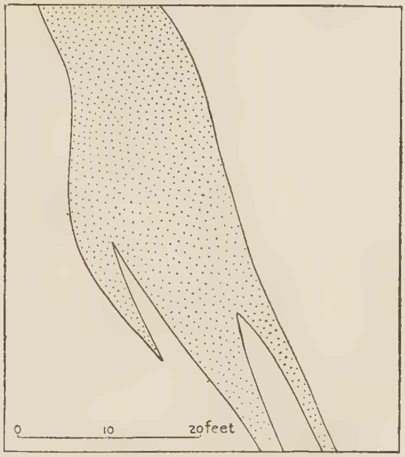

Fig. 4.—Silver Peak, Nevada. Shows forking of quartz lens (in horizontal section), Drinkwater mine. Form indicates intrusive veindike. From J. E. Spurr: Professional Paper 55, U. S. Geol. Surv.; Fig. 39.

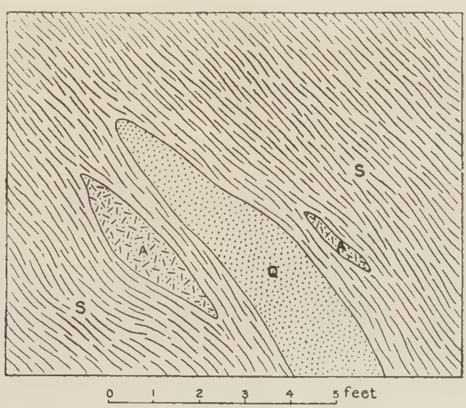

Fig. 5.—Silver Peak, Nevada. Drinkwater mine. Vertical section, showing lenses of quartz (Q) and alaskite (A) in schist (S). Schistosity is parallel to outlines of lenses. From J. E. Spurr: Professional Paper 55, U. S. Geol. Surv.; Fig. 5.

always comformable to the curve of the quartz wall (see Fig. 5). In short, the evidence is quite plain and incontro-

vertible that these quartz lenses, as well as the alaskite lenses (the one passes into the other through all conceivable gradations), have been forced into the sedimentary beds and have not been seriously squeezed since consolidation.

Just what does this conclusion connote and what can we read as to the nature of this quartz magma, and how it comes to be an intrusion rather than the filling of cavities by deposition from water? Our preconception is more in line with the latter theory, although it would necessitate the wildest absurdities of corollary beliefs. Imagine, if you can, the existence of cavities in the schist, of size and shape like the present alaskite and quartz lenses, as shown in the figures—cavities say 50 feet across and 500 feet long and of the same height. Granting that such cavities could exist, why should they be found in the yielding thin-bedded limy shales, and not in the more massive limestones? The idea is plainly preposterous. The intrusions did not find spaces which they filled; they made their own room; they shoved and shouldered their own way in, pushing aside the shaly rock, selected for invasion because the weakest of the sedimentary series. An extraordinary conclusion this, for a quartz "vein," but evidently a true one; the alternatives are not only extraordinary but plainly impossible.

The selection of the form of lenses rather than rectilinear dikes must be for a physical reason; the shove of the intruder and the resistance of the intruded rock were evidently very nearly equal, and the quartz and alaskite magmas had all they could do to win to their present position. The intrusive pressure was not sufficient to hold back the incrushing walls along straight lines for long distances, but could hold back the walls when they were arched like a bridge, and had therefore to support part of their own pressure. Had the ratio of the rock resistance to the telluric pressure of the intruding magma been greater, the magma could not have forced its way in; had it been less, the present lenses would have more powerfully united to form more continuous veindikes. Zones of lenses like that shown

in the Drinkwater mine (Fig. 3) and elsewhere (Fig. 1) represent really intermittent veindikes. It is likely that the original intrusion was more continuous or dikelike, but with weakening of the telluric pressure and the crushing in of the walls, the magma—before crystallization (for the lenses are practically uncrushed and are not sheared)—was squeezed and trapped into these forms.

What, then, was the nature of this magma, and, very especially, by what titanic pressure was it wedged into the shaly sediments?

The magma was a more siliceous form of the granite magma which has been intruded in this same locality. All transitions are found, from biotite granite, through alaskite, to quartz veins. The alaskite contains quartz and feldspar (orthoclase, microcline, and oligoclase-albite), with occasionally a little muscovite, zircon, and pyrite. In the granitic phase (containing biotite), other accessory minerals, such as apatite, magnetite, sphene, and tourmaline, have been noted.

Microscopic study of the alaskite shows that the crystallization was slow and interrupted. The quartz is slightly but distinctly younger than the feldspar. Thin sections show that in many cases the magma became filled with contiguous idiomorphic feldspar crystals, forming a sufficiently rigid skeleton so that it cracked and fissured in places. These cracks and fissures, study indicates, may have been in part formed by contraction in the mass consequent on partial solidification, and in part seem to have been due to movements brought about by pressure on the semi-consolidated magma. Thus the quartz, which always makes up the chief part of the second generation of crystals, besides forming as intergranular quartz (between the feldspar crystals) within the unbroken alaskitic fabric, filled the small fissures (Fig. 6A) and, collecting in larger masses, formed an independent intrusive, in the same sense that the alaskitic magma had done. That the rock, while still soft, was under pressure from the walls, so that it developed

a flow structure parallel to these, is shown in various cases (Fig. 6B and Fig. 7).

The shaly country rock, near the siliceous intrusions, is often filled with siliceous material in seams, lenses, and nodules, and is also altered (mainly by silicification) throughout. Locally, the alteration has produced mica schist, and occasionally the microscope shows hornblende and epidote, as well as quartz and feldspar, in the altered rock. Thin injections of quartz-feldspar material, or of

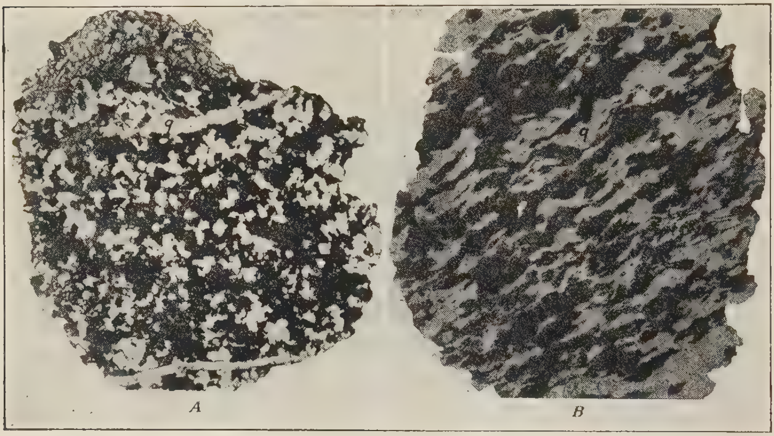

Fig. 6.—Silver Peak, Nevada. Magnified thin sections of alaskite, by transmitted light, enlarged two and a half diameters. The light areas are quartz (*q*); the dark feldspar (*f*), mainly orthoclase. *A*. Veinlets of magmatic quartz in fine-grained alaskite. *B*. Original flow structure in uncrushed alaskite. From J. E. Spurr: Professional Paper 55, U. S. Geol. Surv.; Plate XVII.

quartz alone, are sometimes interlaminated in the schists as between the leaves of a book, making a kind of gneiss. In many cases this alteration of the intruded strata extends only a few feet away from the zone of intrusive lenses of quartz and alaskite, showing its dependence upon this intrusion. We may assume that this alteration is the effect of thinner residues from the crystallization of the main intrusive bodies.

It is not thought that the main magma, from which the alaskite and quartz lenses crystallized, was excessively aque-

FIG. 7.—Silver Peak, Nevada. Photograph of specimen of alaskite veindike (two-thirds actual size, showing full width of veindike) in marble. The marble is not silicified or otherwise altered, indicating the dry or aplitic type of magma. Minerals are almost exclusively quartz (dark) and feldspar (light). Note banded or flow structure parallel to wall, with the separation out of blotches and bands of magmatic quartz. The area within the rectangle is shown enlarged in Fig. 8. From J. E. Spurr: Professional Paper 55, U. S. Geol. Surv.; Plate XIV.

ous. Had it been so it would have lost itself in the schists, instead of forcing them open so that they conform to the intrusive boundaries. Moreover, the largest feldspars in the alaskite and alaskite-quartz, even where the rock is coarsest and most pegmatitic, reach only a few inches in

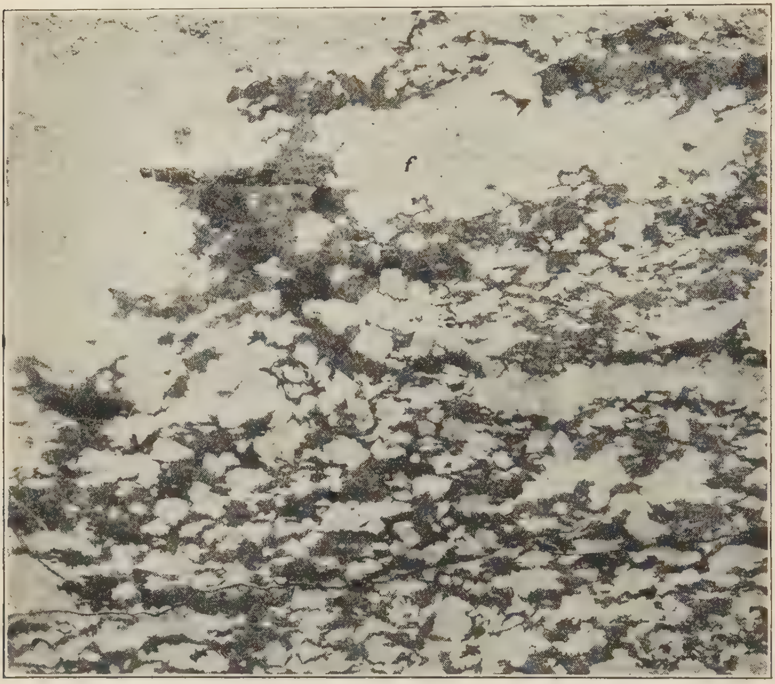

FIG. 8.—Silver Peak, Nevada. Enlargement (two diameters) by photography, of rectangular area in Fig. 7. Dark areas are quartz (q), light areas feldspar (f). Quartz crystallized later than feldspar. Note banded or flow structure, and segregation of quartz. By this process of areal segregation the alaskite veindike is transitional to quartz veindike, all in the same veindike.

diameter, and are not comparable to the giant crystals found in some pegmatites. This is taken to indicate a viscosity and a relative lack of mobility in the magma. Again, a regular dike of fine-grained (aplitic) siliceous alaskite, only six inches thick, was found intrusive into marble (Fig. 7), some 50 feet in the foot wall of the main zone of

intrusion; this dike contains bunches and veinlets of segregated quartz (Fig. 8). Had this magma been an aqueous solution, it would simply have united with the limestone to form lime silicates. From studies which I have made of so-called contact-metamorphic ore deposits at several places in Mexico, I have concluded that the aqueous residual magmas which form pegmatitic deposits in siliceous rocks often form lime silicates, or accomplish what is commonly called contact metamorphism, when injected into limestones.[3] The gold-bearing quartz at Silver Peak, to be sure, though viscous, was somewhat thinner than the alaskite, as is evidenced by the coarser pegmatitic structure.

I have shown that these lenticular quartz veins with schistose wall rock were not formed, by forcible shearing, from continuous veins—that the shearing did not form the lenses. I have, indeed, the idea that the reverse may be partly true—that the schistosity of the wall rock may be in part due to the intrusion of the lenses. As above noted, the metamorphism of the thin-bedded strata to schist is locally directly traceable to solutions residual from the intrusions. Besides this, the physical action of the intrusion may have developed shearing in the wall rock. When an intrusion makes a space for itself ten or fifty or a hundred feet wide, forcing aside the intruded rocks, what becomes of these rocks? I will reason, later on in these essays, that they must make way by flowage—either a plastic movement, or by crushing and granulation, and movement of grain on grain, with or without recrystallization. At Silver Peak the alteration of the shaly limestone to mica schist is local, and was noted only in the walls of intrusive bodies.

As to the problem regarding what force squeezed this siliceous magma into the schist, pressing back the wall rocks with unbelievable power, I find in this simply the problem of igneous intrusion, and on reflection find that the intrusion of a quartz veindike is no more extraordinary than that of a granite or diabase dike—although, to be sure, all these are

[3] *Econ. Geol.*, Vol. VII, No. 5, p. 475.

marvelous phenomena. In 1906[4] Mr. L. C. Graton, now of Harvard, suggested that the gold-quartz veins of the Appalachians were of direct intrusive origin, as I had described for Silver Peak in 1905 ("Genetic Relations of the Western Nevada Ores," Trans. A I. M. E., July, 1905, Vol. XXXVI, pp. 960-961) and again in 1906 (Professional Paper 55, U. S. Geol. Surv., p. 11). Subsequent to Mr. Graton's studies, I had occasion to examine some gold mines in North Carolina, and can, so far as my observations go, confirm his conclusions.

I wish next to describe certain veins in Northern Manitoba and adjacent Saskatchewan. In the first chapter, I referred (p. 84) to some of these veins as intrusive pegmatites and intrusive quartz veins of pegmatitic origin, carrying molybdenite and some gold, and suggested the term veindikes for them and other intrusive veins of this class.

The belt of country in which quartz veins carrying more or less gold have been found in this district is an extended one. The veins lie in ancient (probably pre-Cambrian) greenstones, including altered igneous rocks, probably tuffs and sedimentaries (kneaded coarse conglomerate is one of the striking formations at different places), which have been cut by intrusive granitic rocks. The quartz veins are related to the granite intrusions; especially there is a younger red biotite granite (associated with practically contemporary alaskite), which has evident association with molybdenite-bearing pegmatitic quartz veins, and gold-bearing veins containing tourmaline, on Herb (Wekusko) Lake. This granite and alaskite are intrusive into an older more or less gneissic gray hornblende-biotite granite. All these formations underlie and outcrop at the north edge of a flat-lying dolomite formation of Ordovician age.

The molybdenite-bearing veindikes at Crowduck Bay, on Herb Lake, belong to the younger red granite series, and the feldspars of the pegmatite are of the characteristic red color; they are intrusive into the older gneissic granite.

[4] Bulletin 293, U. S. Geol. Surv., 1906, p. 59.

Certain wide pegmatite dikes which have been intruded parallel to the gneissic structure contain red orthoclase crystals up to several inches long, and have only subordinate muscovite and quartz. The orthoclase mass has been slightly sheared subsequent to the intrusion, parallel to the heavy flow or shear-lines of the gneiss, and in wavy interlacing shear-lines in the feldspar coarse muscovite has crystallized, indicating the action of fluorine on the feldspars.[5]

Molybdenite-bearing pegmatites very similar to these have been described from various places, notably from Maine by Dr. G. O. Smith, later Director of the U. S. Geological Survey.

The relation of quartz and feldspar in these pegmatite-quartz veindikes is shown in various instances. One dike 30 feet wide, of an originally essentially feldspathic pegmatite, with subordinate amounts of intercrystallized quartz and coarse muscovite, has been cut by later quartz in intrusive veinlets, so intricately that the quartz appears on superficial observation part of the pegmatite structure. Locally, however, the quartz has gathered into veinlets in the feldspar several inches wide; and at one point a body of quartz 20 feet wide (containing a small amount of contemporaneous orthoclase and muscovite) lies between the feldspathic veindike and the wall rock.

The main molybdenite-bearing vein consists chiefly of quartz, with locally much coarse muscovite, orthoclase, and molybdenite, all essentially contemporaneous. A little pyrite, arsenopyrite, and chalcopyrite are also present, contemporaneous with the quartz, but in part later than the

[5] At Silver Peak, also, the detailed microscopic study indicated that the muscovite (both coarse and fine) in the alaskite and pegmatite was "universally developed as the result of the alteration of already-formed feldspar by the action of a residual, probably fluorine-bearing magma." The chemical composition of muscovite is such that with the addition of a little quartz, it corresponds to orthoclase; and the presence of a little fluorine shown usually in the analysis of micas indicates that they are formed through the agency of this element.

feldspar. Molybdenite and pyrite occur intercrystallized and contemporaneous; but the deposition of pyrite outlasted that of the molybdenite, since in some cases the former is found along cleavage planes in the latter. This vein carries an average of $2 gold—more than any of the others sampled.

In all these studies of the succession of igneous rocks—alaskites, pegmatites, and mineral veindikes and veins of various kinds—it is important to rid one's self of the preconception (if one has it) of necessarily distinct, separate, and sharply defined formations and events. It is essential to get a perspective. This morning is subsequent to last night, but the subsequence has not the same significance as that of this morning from a morning a million years ago. Between the latter there is a gap of which I know nothing; between the former the events closely overlap and join. In the successive stages of the crystallization of granites, alaskites, pegmatites, and quartz veindikes and veins (and sulphide veins, as I will presently show), a continuous process, in the typical and simple case, goes on. The deposition of certain minerals may be contemporaneous, yet the ranges of precipitation may differ, so that one may outlast the other, and, while contemporaneous, yet may also be in part subsequent and even intrusive into it.

Thus in this series of pegmatitic veins, the three chief minerals are orthoclase, muscovite, and quartz, and although in a broad way all are contemporaneous and parts of a single stage of intrusion, yet in detail the order of crystallization is: first, orthoclase, followed by muscovite (not nearly as important quantitatively as either feldspar or quartz), and last quartz; and it is this difference of stage and span which explains why many of these veins are practically all quartz, while some are mainly feldspar. Quartz is a mineral whose span of deposition is extraordinarily long, as is that of pyrite, and the formation of these may and does go on while many another element of the magma has

its briefer stage of prominence, and disappears from the record.

These molybdenite-gold-bearing veindikes have an unusual interest on account of the gold-quartz veins which have been prospected within a zone a few miles from here, on the shores of Herb Lake, and which have attracted prospectors for several years, on account of the local fine showings, and the high assays of free gold. I examined these gold-quartz veins the year before I visited the molybdenite veins. The two best-known veins are what were popularly known (from the discoverers) as the Campbell-Moore-Hassett vein, and the Hackett-Woosey vein or veins. I shall designate these by initials, for convenience. These veins occur in greenstone gneiss (probably an ancient altered diabasic rock or andesitic tuff), and also in a stratified kneaded conglomerate, both being older than the granitic rocks of the district.

The main H.-W. vein, exposed for about seven hundred feet, does not conform to the schistosity of the country rock, but cuts across it. It consists mainly of barren-looking white crystalline quartz, in a series of bulges and pinches, like a string of lenticular beads, but all connected and forming part of a single vein. The maximum widths on the bulges is 8 or 10 feet, and between these the vein may pinch to mere stringers or even be without visible quartz connecting the points of the lenses (Fig. 9 and Fig. 10). These veins form an interesting transitional type, as regards physical form, between the discontinuous and overlapping lenses in schist (p. 90) and the regular tabular vein form. In this case no peculiarity or influence of the wall rock can be appealed to as explanation of the form of vein, a point which is further proved by comparison with the main C.-M.-H. vein, which has the same general form, but which lies parallel to the schists.

The other veins of this section have the same physical peculiarity, and some of the lesser and weaker ones are small lenses with no apparent continuity. The main veins

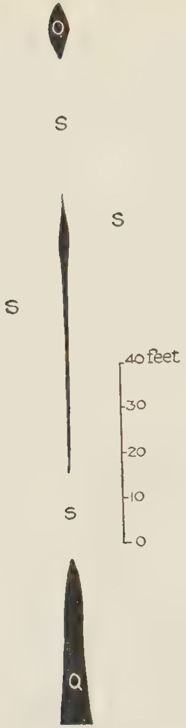

FIG. 9.—Herb Lake, Canada. H.-W. No. 2 auriferous quartz vein in pre-Cambrian schists. Transitional type between ordinary fissure vein and quartz lenses. Shows origin of lenses by trapping of ore magma between closing-in fissure walls before quartz consolidation. Q, quartz; S, schist.

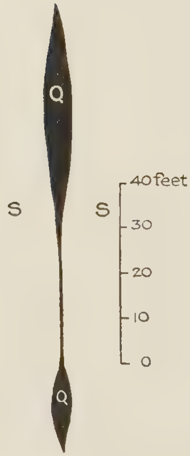

FIG. 10.—Same as Fig. 9. Shows another section of vein outcrop; horizontal plan. Q, quartz; S, schist.

evidently penetrated along definite strong fractures or channels, and the only reason that appeals to me for the pinching and bulging into connected and aligned lenses is that mentioned in discussing the Silver Peak lenses—namely, that the phenomenon is the result of the balance of intrusive pressure of the vein magma and the resistant and incrushing pressure of the rock walls; and that the bulging and lenticular shape offers greater resistance, with its arched walls, than do parallel walls. A consideration of the sketches shows that the theory cannot be entertained that the lenses were formed by the slipping of one wall of a curved fracture, past the other, a theoretical (and entirely theoretical) possibility which has been advanced to explain the swellings and pinchings of veins, as for example by Becker with reference to the Comstock lode.

It is therefore my conclusion that these gold-bearing veins are closely allied to, and are in fact almost a variation of, the gold-molybdenite-bearing veins of Crowduck Bay, above described; that they represent a slightly later stage; and, like the above-mentioned veins, that they consist essentially of what may be called magmatic quartz—the quartz of pegmatites and pegmatitic quartz veins, which acts like an intrusive, forming veindikes. Veinlets of quartz lying near these gold-bearing veins are pegmatitic, carrying some coarse muscovite and orthoclase; and even the main veins often show some muscovite along the edges. Black tourmaline also occurs sparingly in the veins. In at least one case noted, free gold was crystallized with and apparently contemporaneous with tourmaline. Tourmaline[6] is a mineral common as an accessory in granitic rocks, and denotes the presence of the volatile element boron in the solutions or magma from which they have been formed.

In these veins the metallic minerals are almost entirely deposited along parallel fractures which are later than the

[6] Tourmaline is a complex silicate of boron and aluminum.

quartz of the veins. In the H.-W. vein, these fracture planes run *transverse* to the quartz vein, and frequently fault it, with a maximum horizontal displacement of three or four feet. Most of the free gold is probably of later deposition than the quartz; also, there is locally considerable subsequent arsenopyrite and a little copper pyrite. Evidently the deposition of free gold and arsenopyrite was connected with the quartz deposition, and followed it closely, so that some of the quartz may be contemporaneous with some of the gold and arsenopyrite, but not much: in other words, the quartz deposition and the metallic minerals deposition represent distinct stages of the same process of vein formation. It is to be noted that although the later fractures are transverse to the quartz vein, the subsequent deposition of metallic sulphides is confined to the quartz and the immediate wall rocks, showing that the later solutions ascended along the same general channel which gave access to the quartz veindike. Also, the wall rocks are impregnated by arsenopyrite, which has formed at least partly by replacement. Along the strike of the vein, in stretches where there is practically no quartz, between the lenticular quartz bodies, there is often heavy arsenopyrite impregnation of the schist. The arsenopyrite is in part auriferous.

In the C.-M.-H. vein, which otherwise is similar to the H.-W. vein, the subsequent fractures are *parallel* to the vein, and there results the familiar "ribbon structure" so often found in gold-quartz veins of this type, and which, indeed, may be said to be almost typical of them. In these longitudinal fractures (which sometimes show slickensidings) arsenopyrite and, not infrequently, free gold have been deposited. This ribbon structure is well known in the veins of California and the Appalachian region.

I wish to call especial attention to this difference of stage, in these veins, between the deposition of quartz, and of metallic minerals with little or no quartz, as it is a characteristic one, which will be found in many veins, formed under different conditions; and illustrates my remark in

the first chapter, that the association of quartz and metallic minerals in veins is an adventitious one.

Now, just as in the feldspar-quartz pegmatite, the slightly later quartz not only was found to invade and crystallize intimately with the slightly earlier feldspar, but, drawing off by itself, to form separate veindikes composed almost entirely of quartz, such as constitute the quartz veins which we have just described: so in the case of these quartz veins which show distinctly even though slightly later metallic minerals (in this instance more or less auriferous arsenopyrite and free gold), with little or no quartz, may not these minerals be drawn off along separate fractures and form independent veins? As a matter of fact, the type of massive arsenopyrite veins, usually more or less auriferous, and accompanied by little visible quartz, is a common one. If we revert to the Silver Peak district, we find at least one very good example.[7]

At the Great Gulch mine, in this Silver Peak district, the ore is a massive auriferous arsenopyrite, which is later than the slightly auriferous quartz lenses, typical of the district, and is also of distinctly higher content of gold. The arsenopyrite streaks have a maximum width of one or two feet, but are usually much narrower. By preference they follow the walls of quartz lenses, but also occur in cross-cutting streaks (Fig. 11). The ore has originated partly by replacement, especially of the calcareous schist wall rock and of the alaskite.

The localization of the Great Gulch arsenopyrite veins along the walls of quartz lenses has a similar explanation to that of the thin platy streaks of arsenopyrite in the quartz veins at Herb Lake, in Manitoba: not only is it probable that the solutions rose from the same general source, but the strain which took place in each case subsequent to the crystallization of the quartz found no formation so susceptible of fracturing as the quartz itself. In the schist wall rock in both cases, the slight movements were taken up

[7] *Professional Paper* 55, U. S. Geol. Surv., pp. 66, 117.

by mashing and flow, and the most favorable channels formed were those in the hard and brittle quartz. There is at the Great Gulch mine a marked preferential location for the arsenopyrite streaks along the hanging wall of the quartz lenses, indicating rising solutions (Fig. 12). The

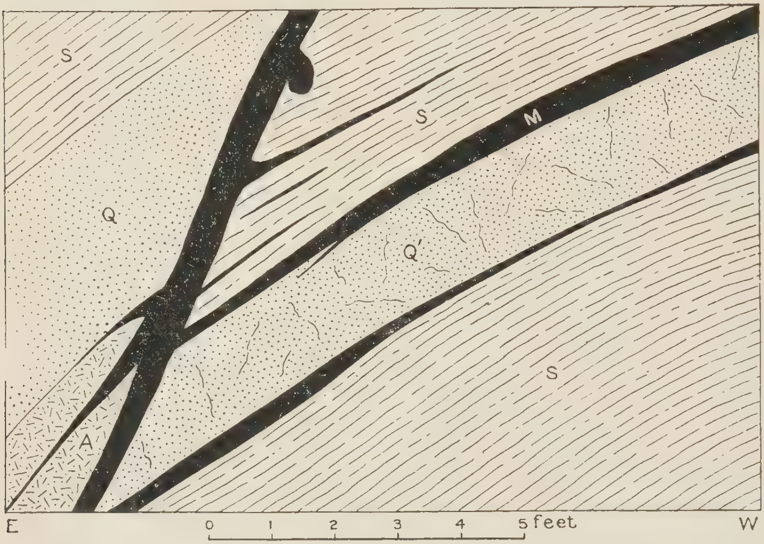

FIG. 11.—Great Gulch mine, Silver Peak, Nevada. Shows faulting of gold quartz vein *(Q)* and subsequent deposition of auriferous arsenopyrite *(M)*. Of the wall rocks, S=schist, pre-Cambrian; A=alaskite, intrusive into the schist. After J. E. Spurr: Professional Paper 55, U. S. Geol. Surv.; Fig. 18.

upward pressure of the solutions was held back by the relatively impervious blanket of schist hanging wall, which dammed these at the time of crystallization.

Let us pass now to the other end of this prospected auriferous belt in Manitoba and Saskatchewan, to Beaver or Amisk Lake, on the Saskatchewan side of the boundary, where the first discoveries of gold were made and the first prospecting was done. The main formation here also is green schist, apparently partly of igneous and partly of sedimentary origin. Sheared and kneaded conglomerate like that at Herb Lake occurs also at Beaver Lake. The

veins are of the same crystalline white quartz, but less persistent. While some of them are persistent for several hundred feet without break, others (like those on the Wolverine claims) are simply a zone of short quartz lenses with little or no apparent connection. The largest lenses seen are about five feet wide and 40 or 50 feet long. The values are largely in sulphides, which occur in small quantities along distinctly later sheetings, as at Herb Lake. In some veins these sulphides are mainly arsenopyrite, as at Herb Lake (although not so abundant); in others copper pyrite, pyrite, and galena occur. Copper pyrite is perhaps the most conspicuous sulphide. The veins, lenses, and subsequent sulphide-bearing sheetings all run parallel with the schist.

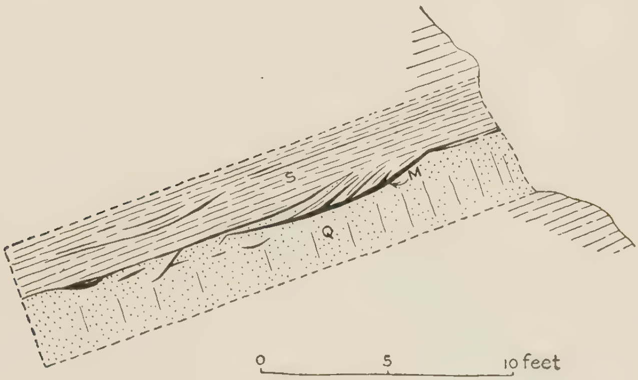

Fig. 12.—Great Gulch mine, Silver Peak, Nevada. Longitudinal vertical section of mine incline, following gold quartz vein (Q) in schist (S), with auriferous arsenopyrite (M) subsequent to the quartz, in the hanging wall of the vein. This position indicates ascending solutions. After J. E. Spurr: Professional Paper 55, U. S. Geol. Surv.; Fig. 17.

If the subsequent arsenopyrite which occurs in fractures in the auriferous quartz veins, as on Herb Lake, may be drawn off and form independent veins, as at the Great Gulch mine, in Nevada, should not the same thing occur with the other metallic sulphides—chalcopyrite, pyrite, and galena? As a matter of fact, very large deposits of sulphides, with very little quartz, are characteristic of the

whole belt between Beaver Lake and Herb Lake. Passing over the commoner types, I shall describe an unusual one which is of extraordinary interest.

At Schist Lake, ten or fifteen miles east of Beaver Lake, and between it and Herb Lake, I had part in the discovery of the Mandy mine, which was later prospected, drilled, developed, equipped, and mined under my direction. The ore deposit is a sulphide lens in green schistose rocks, which are probably of tuffaceous origin. The only difference between the foot wall and the hanging wall is that the latter is slightly more schistose. The ore occurs in a narrow especially schistose zone lying in more massive greenstone schist. Three-quarters of a mile from the mine is a large granite intrusion.

In general the ore lens shows massive blende and chalcopyrite, as well as pyrite, in relations which will be described later. On the surface the lens is blunt at the south end, where the schist arches over it, and the ore pitches down, with the schist as a roof; at the north end the main lens tails out into a crack in schist, entirely unaffected by mineralization or allied phenomena, which crack loses itself in the finely laminated schist zone. The length of the lens is about 200 feet, with a well-sustained width of nearly 40 feet (Fig. 13). It wedges out with depth, and in about 200 feet, more or less, practically comes to a point or becomes inconspicuous (Fig. 14 A and B). Inasmuch, however, as the cross-section indicates that a large part of the vertical extent of the lens has been removed by erosion, it is evident that originally the orebody had much greater vertical than horizontal dimensions; it must have been a body at least 400 feet high, by about 200 feet long, and 30 to 40 feet wide in the center, tapering above and below.

The lens consists of practically solid sulphides, with very little visible quartz. Massive chalcopyrite and zincblende are the most conspicuous elements, and though often occurring mixed and interlaminated, as will be described, occur mainly in separate portions of the lens, so

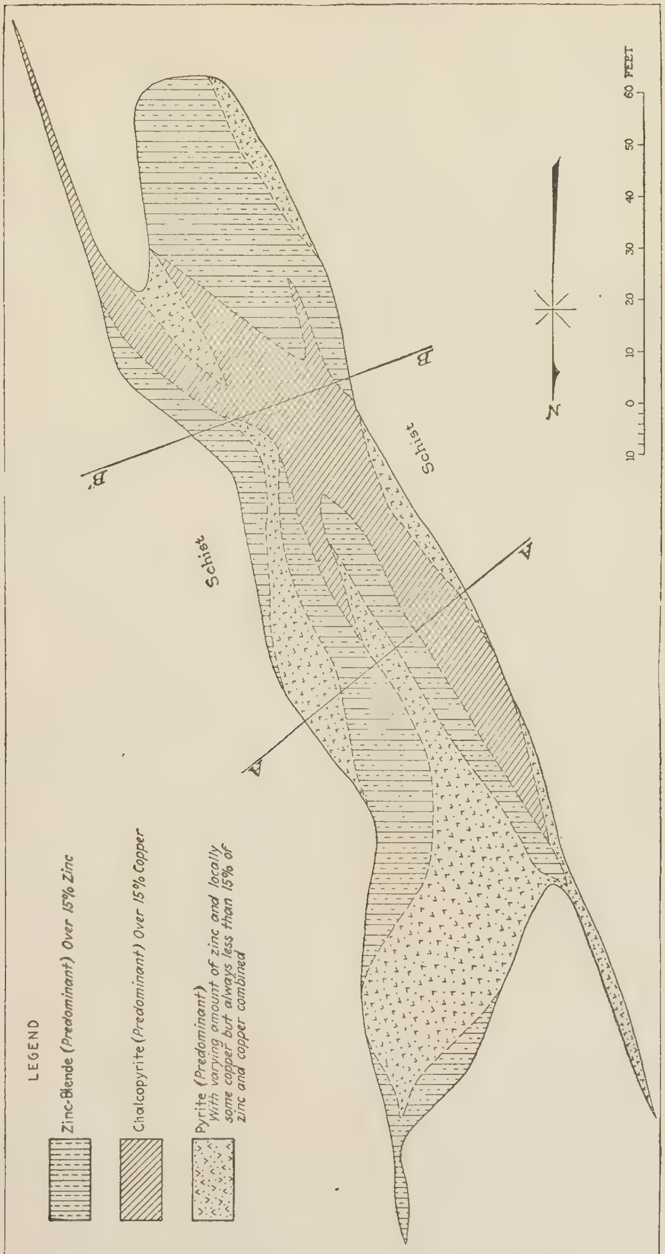

Fig. 13.—Mandy mine, Schist Lake, Manitoba, Canada. Surface plan.

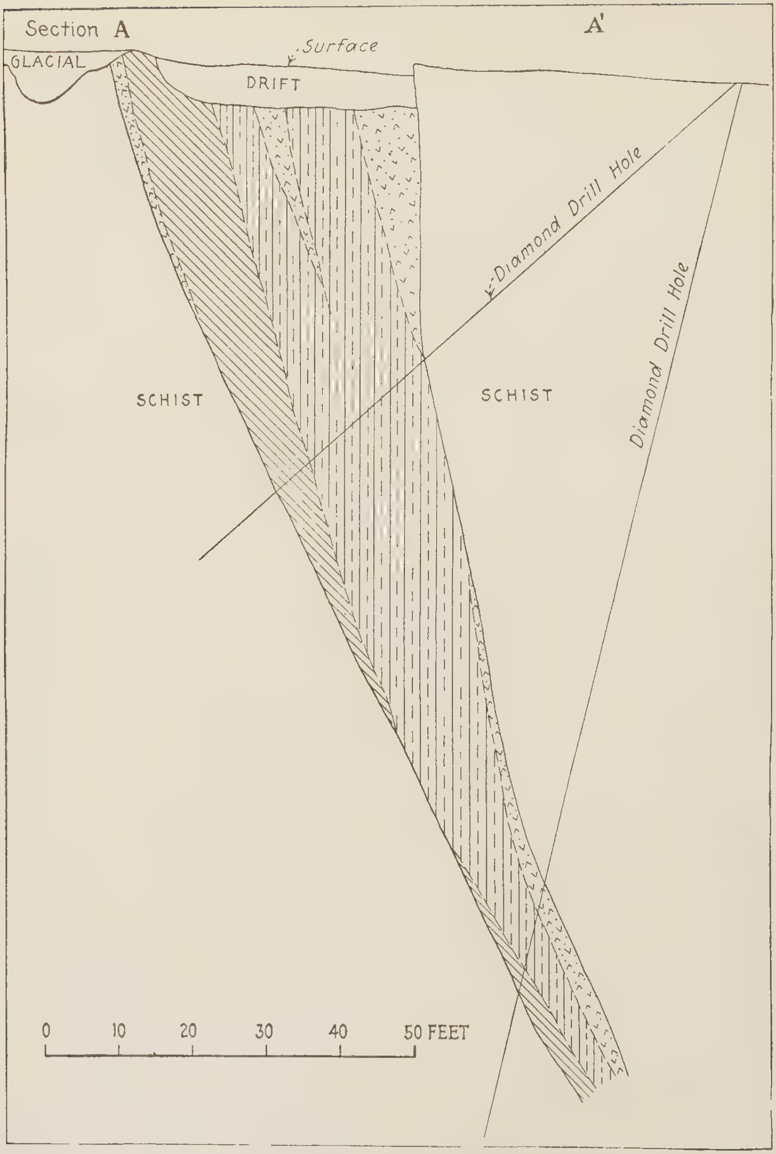

FIG. 14-A.—Mandy mine, Schist Lake, Manitoba, Canada. Vertical cross-section. For legend see Fig. 14-B, p. 113.

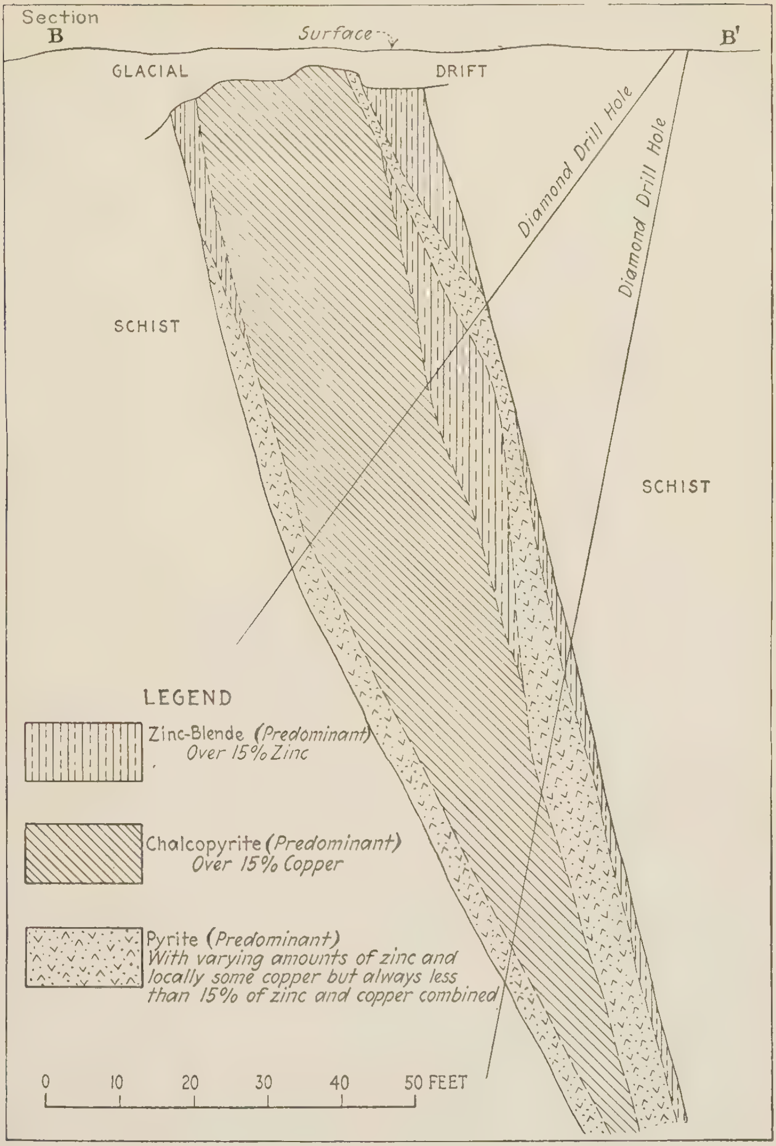

FIG. 14-B.—Mandy mine, Schist Lake, Manitoba, Canada. Vertical cross-section.

that it has been possible to mine the high-grade chalcopyrite separately, and ship it to the smelter. This chalcopyrite is fine and even grained, with the color and texture of bronze; the massive blende has the same fine and even grain, its fractured faces, except for the dark-red color, somewhat resembling cast iron. The general relations are expressed, so far as a sketch or map can do it, in Fig. 13. There is, however, much fine interlamination of chalcopyrite and blende, in varying proportions.

From a close study of the surface exposures; later of the open cuts from which the ore had been quarried; also of broken chalcopyrite ore stacked up for shipping, the following sequence of deposition was made out:

1. The earliest vein or veindike formation consisted of a very unimportant amount of white quartz veinlets, and veinlets of coarse pyrite.

2. Massive fine-grained blende, dark red, dense and homogeneous throughout as to grain and color, was introduced. It forms a lens, with a vertical cross-section double that of the horizontal. This blende locally contains many streaks and bands of cupriferous pyrite (paler yellow in color and containing much less copper than the later chalcopyrite), intimately drawn out and interstreaked with the blende in such a way as could only have been done by flow. This shows that the blende and cupriferous pyrite was in a plastic form, as a stiff paste. This zinc ore carries up to around 30 per cent zinc, when sampled in five-foot cuts.

3. The blende ore was split open, and high-grade chalcopyrite introduced, along a line a little diagonal (as seen on the horizontal surface section) to that of the blende (with cupriferous pyrite) lens. This chalcopyrite is massive and homogeneous throughout as to texture and color, except for streaks and bands of blende like No. 2. This ore assays up to around 25 per cent copper, when sampled in five-foot cuts. Thousands of tons mined and shipped averaged around 18 per cent copper.

Chalcopyrite and blende have the same texture and homogeneity, but even where interbanded, the distinction between the streaks is very sharp. The fine lines and bands of blende are so intimately interstreaked with the chalcopyrite, and the streaks are drawn out in such perfect

Fig. 15.—Mandy mine, The Pas district, Manitoba. Sketch of block of ore, on contact with wall rock. *a,* Dark green schist (wall rock); *b,* coarse quartz vein in schist (altogether antedates orebody); *c,* chalcopyrite with fine lines of dark zinc-blende, showing flow structure. Ragged contact shows that flow lines in *c* could not have been induced after intrusion, but must have been due to the flow of plastic intrusive sulphides.

parallelism, that the conclusion is that the structure is the result of flow, and that the ore could have been introduced in no other way than in plastic form, as an intrusive mass. Though the blende streaks in the chalcopyrite are identical in character with the massive blende (streaked with pyrite) above described (No. 2), they do not belong to the same

period of injection, for the No. 3 mass forms branching irregular dikelets (veindikelets) in the blende of No. 2. It also cuts the schist wall rock in the same way, showing not only intrusion, but that there has been no movement, flowage, or shearing in the orebody since consolidation (Fig. 15). There are, in the chalcopyrite, occasional inclusions of schist, of coarse quartz, and of coarse pyrite (the two latter are of deeper or "abyssal" origin—they are not represented in the present orebody). These inclusions show no trace of flow or other parallel structure, but the flow lines of the chalcopyrite (with blende streaks) curve around the inclusions as does the flow banding of rhyolite around inclusions.[8]

Therefore both main periods of ore deposition, first of blende and later of chalcopyrite, were intrusions of plastic sulphides. Certainly the intrusions were stiffer than is usually the case in most igneous rocks, which are intruded as solutions and crystallize after intrusion; the viscosity was like that of tar, and is analogous to that of those rhyolities and obsidians which show a fine flow-banded structure. Some of the streaks of pyrite noted in the blende show waving and even crenulation as the result of

[8]A thin section of the ore, when examined under the microscope, shows a good deal of fine crystalline quartz, in small nests of crystals, in the chalcopyrite. The quartz crystals are interlocking, unbroken, and with no uniform orientation—there is no evidence of crushing or strain. The chalcopyrite seems to be later than the quartz—it has in many places penetrated the quartz between the crystals, and, indeed, invades the quartz bunches irregularly, much as a rhyolite magma invades the partially "resorbed" quartz phenocrysts.

Fragments of wall rock seem entirely altered to chlorite. The contact between sulphide and altered greenstone is sharp, but at the very contact a thin zone shows trituration along the contact—small broken and rounded fragments of the sulphide are mixed with the chlorite. This zone, however, is very thin, and locally the sharp line of contact cuts across the chloritic lamellæ of the greenstone inclusion.

Altogether, the section studied supports the view of the intrusive nature of the chalcopyrite, and indicates that the still fluid chalcopyrite carried along in it some earlier-crystallized quartz; also, that the friction of the intrusion brought about a trituration of the wall, in which trituration the outer edge of the hardened sulphide was involved.

flow and backflow, and the effects are different in neighboring parallel bands, showing that certain streaks of the ore flowed slightly faster than adjacent streaks (Fig. 16). But the magma, if I may so call it, was not stiff enough for rupturing; there are absolutely no phenomena of brecciation.

Yet, if this is indeed an intrusion (and I see no escape from this conclusion) it differs from the usual igneous rock intrusion in a very important particular—that of shape. This solid, massive, short, and broad orebody, shaped like one of those flattened and elongated pebbles which we find

FIG. 16.—Mandy mine, The Pas district, Manitoba. Sketch of block of ore; one-fifth natural size. *a*, Massive blende; *b*, pyrite, somewhat cupriferous. Shows crenulation of some of the *b* streaks to a greater degree than others, indicating differential flow in different streaks.

in ancient conglomerates which have been subjected to pressure and flow, is, so far as exploration has yet shown, alone. Prospecting along the surface for some distance beyond each end of the orebody has revealed no more ore, nor have drill holes discovered any in depth, although I still think it does exist, and that further drilling in depth is warranted.

In discussing the lenses at Silver Peak, I pointed out the probability that the shape was due to the crushing in of the schist walls, as the pressure which effected intrusion diminished, and to the trapping of pockets or lenses of the intrusive material. But why, in this case, is not the same

form as characteristic of igneous rock intrusions, as it certainly is not? Must it not be dependent upon the physical difference between the veindike magma and the dike magma?[9]

Both the copper and the zinc ore alike contain about a tenth of an ounce of gold and two ounces of silver per ton, and analysis shows a tenth of a per cent of lead.

4. The sulphides above described were fissured and cracked, and along the cracks were deposited: (a) zinc-blende; (b) pyrite, carrying a little copper, the blende sometimes being the first deposition in a fissure, and lining the walls, while the center is filled with pyrite (Fig. 17). This No. 4 deposition contains about 50 per cent of inter-crystallized quartz, whereas 2 and 3 (the massive zinc-blende and chalcopyrite) contain practically no visible quartz, although they show streaks of it under the microscope in the two specimens so examined. The average of many determinations of the whole lens shows 8 per cent

[9] Nevertheless, intermittent igneous dikes are not so very rare, as I recall, from my own experience and from the literature. Such dikes terminate along their strike; then in a little distance they begin again; and this recurs repeatedly. In connection with this, see for example, James Geikie, "Structural and Field Geology," 1920, p. 211. He observes:

"Dykes often wedge out suddenly, both in lateral and vertical directions. Traced across country, they not infrequently seem to die out, and then after a shorter or longer interval they may as suddenly reappear. When a dyke of this kind is represented upon a map, therefore, we have the appearance of two or more dykes following each other along the same line. That the apparently separate dykes, however, are really portions of one and the same intrusion, has now and again been demonstrated."

I apply my theory (as above stated for the intermittent veindikes and disconnected but aligned lenses of quartz and pegmatite) to these intermittent igneous dikes also, at least to some of those that I have personally seen. Pressure of the walls has separated the now disconnected segments, after the injection of the fluid magma, but before consolidation. The reason that this intermittent (and consequent often lenticular) structure is more characteristic of quartz, pegmatite, and other veindikes lies perhaps in the superior gaseous content and consequent gaseous tension of the latter; and this means that the magma has more telluric pressure to lose on incipient consolidation, and hence is crowded in more severely by the pressure of the walls.

insoluble material, which is probably mainly quartz; but this would include the admixture of the No. 4 deposition, which is very common.

The amount of pyrite (No. 4) which has thus become mixed with the earlier sulphides, or has replaced them, in some portions of the lens becomes so great that it is altogether predominant; and here we find (as shown in the geologic plan and cross-section) predominantly pyritic

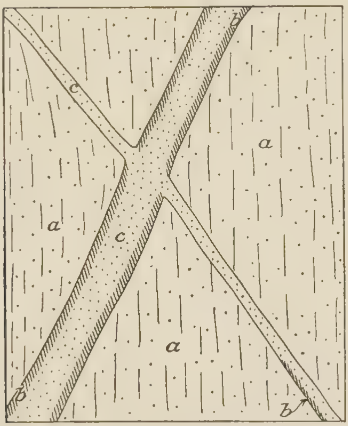

FIG. 17.—Mandy mine, The Pas district, Manitoba. Sketch of block of ore, about actual size. *a*, Chalcopyrite with finely interbanded zinc-blende; shows flow structure. *b*, Black zinc-blende (and pyrite); *c*, pyrite; *b* and *c* fill fissures in *a*, *b* being an earlier deposit on the walls. Shows stages of sulphide deposition: in general, (1) copper pyrite, (2) zinc sulphide, (3) pyrite.

bodies, although containing various amounts of zinc-blende and even of chalcopyrite. Apparently, however, the pyritic solution attacked and replaced blende preferentially and chalcopyrite much more difficultly.

The succession of deposition of the No. 4 veinlets as above described perhaps suggests precipitation from solutions in the more ordinary manner of vein formation, as we conceive of it; yet the close relation of these solutions to the earlier stiff sulphide injections is indicated by the similar mineral composition, so that the difference may be viewed

as one of relative concentration, the last solution having been more siliceous and presumably more aqueous.[10]

It follows, of course, from the history of the lens as above outlined, that the successive stages are mixed in varying proportions. The classification which I have made in the accompanying plan and cross-sections has seemed to me best, both from a practical mining standpoint and that of the student of ore deposits. It is based on most careful systematic ore sampling and analyses in ten cross-trenches, before mining began. The cross-sections have (each) one of these trenches at the surface, and two diamond-drill holes, as data.

The wall rocks of the Mandy ore lens show very little silicification or impregnation by sulphides. In the walls of the massive blende and chalcopyrite bodies there appears to the eye to be no replacement, and the same is true of the schist inclusions in the ore. Nevertheless, certain thin zones of rock explored by the drill holes do show replacement of the schist by disseminated pyrite and cupriferous pyrite; and this we may suppose to be the effect of the latest stage of mineralization described above as No. 4.[11]

[10] The complex magmatic history of this orebody suggests in a way the history of some igneous rock intrusions. I do not wish to anticipate, but after the reader has studied Chapter VII, I wish he would refer back to the Mandy description, and observe that two successive intrusive aplitic ore magmas have been followed by a pegmatitic ore magma.

[11] Since the above was written two articles of interest, describing the Mandy and Flin Flon mines, have appeared in *Economic Geology,* Vol. XV, 1920, Nos. 5 and 7. In the former number Dr. E. L. Bruce ascribes the banding of the chalcopyrite-blende ores of the Mandy to an original schistose structure, which the sulphides have replaced. I cannot accept this theory, for which no evidence is offered. The form of the orebody is believed to be possibly due to the replacement of a drag fold in the schist. The distribution of the chalcopyrite, whose diagonal later intrusion as shown in Fig. 13 furnishes the extensions of the orebody which led Dr. Bruce to this hypothesis, quite negatives it. Dr. Bruce agrees with my conclusions that the ore is genetically connected with the granitic intrusion. In the second article ("Some Canadian Occurrences of Pyritic Deposits in Metamorphic Rocks"), Mr. George Hanson notes in the Mandy ore the following metallic minerals, named in the order of their deposition: pyrite and arsenopyrite; sphalerite and chalcopyrite; galena. He notes,

Many sulphide deposits have been prospected in this belt, their distribution covering the entire belt, but no other deposit like the Mandy, with its high-grade, massive chalcopyrite and zinc-blende, has been discovered. Therefore, the Mandy is the only mine which has been worked, and its working was made possible by the mining of the chalcopyrite separately, leaving the zinc ore.[12]

Most of the other sulphide deposits of the region consist of vast amounts of pyrite and pyrrhotite, with very small amounts of the more valuable sulphides; they are usually far larger deposits than that at the Mandy. The one which carries most of the valuable metals, and is at least a potential orebody of vast dimensions, occurs a few miles north of the Mandy orebody, in the direction indicated by the long

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in the scanty gangue, quartz, calcite, dolomite, and chlorite. He finds that the gold in the ore is contained in the chalcopyrite, and the silver in the sphalerite. In the wall rock he holds that, as secondary minerals developed by the ore solutions, sericite, carbonates, pyrite, chlorite, quartz, and rutile have formed. From the presence of arsenopyrite, he concludes that intermediate to high temperatures prevailed during ore deposition. Mr. Hanson believes that the banding of the chalcopyrite-blende ore in the Mandy was not due to post-ore deformation or movement, but that slight shearing went on during the deposition of this ore, thus accounting for the banding. This, it will be observed, is essentially classifying the banding as a flow structure, just as I do. In the last stage of predominantly chalcopyrite deposition, he believes the ore filled open fissures, whereas the earlier ore was due to replacement.

In the Flin Flon ore he finds the same sulphides as at the Mandy: and he concludes that the ores were deposited "under conditions of intermediate to high temperatures by hydrothermal solutions, which may have been given off from an underlying granite magma."

I am grateful to Mr. Hanson for calling attention to the arsenopyrite in these ores, as this fills in somewhat my argument as to the close relation of the gold-bearing arsenopyrite ores of Herb Lake and the copper ores of the Mandy. His views are well worth keeping in mind, although they differ somewhat from mine. As to the banding, both views call for flowage during the consolidation of the sulphides.

[12] The chalcopyrite is entirely primary, even on the outcrop; it has not been enriched by the secondary action of surface waters. This district has been thoroughly glaciated, and whatever effect of surface alteration may have existed in the outcrops has been gouged off at the Mandy, so that the fresh hard sulphides outcrop.

horizontal axis of the Mandy ore and by the schistose zone in which it lies. It is called the Flin Flon orebody, and was the first sulphide ore in this district to which attention was called, having been discovered just before the Mandy. The Flin Flon orebody lies along the shore of a small lake of the same name. The orebody consists of massive sulphide, or of sulphide replacing in all stages a steeply dipping greenstone schist. The length of the mineralized area is around 2,000 feet, and the width appears to be up to 100 or 200 feet in places.

The general outline of the mineralized body seems roughly lenticular. I visited the mine only in 1915, when it had been trenched but not drilled, as has been repeatedly done since then; I have not had access to these subsequent data. There is a little very superficial leached gossan here (which is not the case at the Mandy mine). It overlies sulphides which are a few feet below the surface; and it shows that the ore contains up to 50 per cent quartz, which would hardly be thought from inspecting the heavy sulphides. A great deal of the gossan also shows principally soft yellow limonite.

The superficial samples showed gold, silver, copper, and lead, the principal values being in the first three. The proportion of metals differs from that in the Mandy in that there is little zinc at the Flin Flon, whereas at the Mandy it is so important and high grade; and in the greater proportion of galena at the Flin Flon, a mineral which is rare at the Mandy. In addition, the ores of Flin Flon are of low grade, whereas those of the Mandy are of high grade; in this respect they are extremes. At the Flin Flon, also, the gold and silver values are more important relative to the copper value than at the Mandy. The total values are such as to encourage drilling and other investigations, but to make capital hesitate at encountering the large outlay which would be required for equipment for mining, beneficiation, and transportation.

Though the Flin Flon orebody and the Mandy body are

thus closely associated, and evidently closely connected genetically, it will be noted that the one is very big and of very low grade, and the other relatively small and of unusually high grade. Moreover, a cursory examination of the former did not suggest a complex origin and history: all the ore appeared to have been deposited mainly by replacement, with no evidence of intrusion. Therefore the Flin Flon body is thought to represent the same general conditions of deposition as the No. 4 stage of the Mandy.

Another sulphide body of evidently the same general type as Flin Flon occurs not many miles away from these, at the mouth of Pineroot River, on Lake Athapapuskow. Here, in greenstone schist, are parallel mineralized zones, originating by replacement and accompanied by a certain amount of silicification. These zones show pyrite, blende, and chalcopyrite, which sometimes occur in streaks of solid sulphide; and some quartz. They had not been sufficiently prospected at the time of my visit.

Some miles further east, on the shores of Copper Lake, there occurs an immense deposit of massive pyrite and pyrrhotite, showing only traces of valuable metals. This I traced for nearly a mile in length. These sulphides occur in green schist, and have apparently originated mainly by replacement. On the borders of the sulphide body there is a great deal of silicification as well as partial pyritization of the wall rock.

Further east at Sandy Lake, which adjoins Herb Lake [13] on the west, there is a large pyritic body at the contact of intrusive granite and greenstone schist. I conducted some test-pitting on this deposit, but found practically no traces of the valuable metals.

All these sulphide deposits except the main ore deposition at the Mandy, I feel obliged to repeat, have evidently formed mainly by replacement. Many of them are immense deposits, showing the transfer of enormous amounts of iron and sulphur, and a great deal of silica, to form them.

[13] P. 100.

Though carrying traces of gold and silver, and in the case of the Copper Lake deposit, of nickel, many of these show no appreciable amounts of valuable metals, though the Pineroot River occurrence, and especially the Flin Flon body, become at least potential ores. The general form of these deposits has not been determined, but they are very broad in proportion to their length, so that they are chunky and irregular, if not lenticular. Such deposits are not veindikes, in which they differ from the Mandy copper-zinc sulphide body, from the gold-quartz veins of Beaver and Herb Lakes, and from the molybdenite-gold-bearing pegmatitic veins of Crowduck Bay; but very clearly they represent a stage of deposition from magmatic solutions—a stage, if we are right, related to the last stage at the Mandy, which followed the sulphide veindike intrusion; while all the sulphide deposits seem to represent a major group whose period immediately succeeded the deposition of the quartz veins. The solutions which deposited the larger sulphide deposits must have been heavily charged with iron, sulphur, and silica, with, at some stages, a limited amount of gold, silver, copper, lead, and zinc. They penetrated and saturated the schist in certain localities and replaced it.

The regional association of gold-quartz veins or veindikes with copper ores, the latter immediately subsequent to the former, which we have noted in this Manitoba-Saskatchewan district, is a very common and characteristic one. We find it, for example, in California (in Shasta County), and in North Carolina. We may return to this discussion later.

I have been intensely interested in the Mandy intrusive type of sulphides: I believe that it may belong to a class which has been repeatedly described by excellent authorities, especially in Scandinavia, as eruptive bodies of pyrite and copper pyrite.

The purpose of this chapter, let us remember, is to inquire into the manner of formation of certain mineral veins, and how they come to the situation where we find them; and

I have shown how certain types of gold-quartz veins and even of sulphide deposits have forced themselves up as veindikes, and crystallized with little or no concentration other than that which was accomplished below in the laboratory of the parent magma; and how, residual, perhaps, from these veindike magmas, we perceive a thinner, more pervasive solution, which can slip through rocks without pressing them asunder, permeate them, and exchange most insidiously their substance for its own.

I wish in this connection to describe certain veins in the Georgetown district in Colorado, and the adjacent districts of Idaho Springs and Empire, which I studied in 1905, with the assistance of Mr. George H. Garrey, while the general geology was studied by Dr. Sydney H. Ball. The observations which I shall detail have a direct bearing on the nature of the solutions which deposit the massive sulphide veins and ore deposits, with earthy gangue relatively inconspicuous or practically lacking; and this is a type which is common. I will briefly sketch the background of the problem before setting forth the pertinent facts.

These Colorado mining districts lie in the Archæan, in that mass of the most ancient rocks we know, which formed an island where now is Colorado, in the first ocean of which we have a clear record. In detail the mass of rocks is a complex of crystallines—gneisses, schists, granites, and pegmatites, the last two representing many successive intricate injections of granitic magma into prehistoric (in the geologic sense) formations, which were in part at least sedimentary. In the earlier Tertiary, numerous alkaline-siliceous igneous dikes penetrated this mass, and closely associated with the dikes came the formation of many mineral veins. The veins are separable into two distinct types: (1) galena-blende veins with more or less pyrite, chalcopyrite, gray copper, and polybasite; (2) pyritic ores containing chiefly pyrite, cupriferous pyrite, or chalcopyrite, and a subordinate amount of galena and blende. The former type are silver-bearing veins without important

amounts of gold, and the latter gold-bearing veins with or without silver. The former type consists of essentially sulphide veins, containing subordinate or inconspicuous quartz or other gangue; the latter usually contains a great deal of quartz, which in some cases is predominant.

The different types occur principally in two distinct areas; the galena-blende veins preponderate greatly in the Georgetown area, and the pyritic veins in the region west of Idaho Springs. The two vein-types are associated with distinct dike-types occupying the same relative districts; in the district characterized by predominating silver-bearing galena-blende veins the dikes represent a siliceous granitic magma—alaskite porphyry and granite porphyry being the most abundant types; whereas in the district characterized by predominating auriferous pyritic veins the dikes represent an unusually alkaline siliceous magma, being classified by Mr. Ball as bostonite, alaskitic quartz monzonite, biotite latite, and alkali syenite porphyry. The veins of the first (galena-blende) type are invariably younger than the associated dikes; those of the pyritic type are also usually younger than the dikes with which they are associated, but are older than some of the dikes. An illustration of the last case occurs at the Stanley mine, where a dike of bostonite porphyry in the Archæan pegmatite and gneiss was split open, and the opening filled by an auriferous quartz vein containing mainly pyrite as the metallic mineral; and later both dike and vein (both followed the same successively reopened fissure) were again split open by an intrusion of latite.

The veins of both types follow and occupy fault zones of slight displacement.

Many of the veins are plainly due to impregnation and replacement of crushed rock or of fault gouge along the fissure zone, as is shown by careful studies, as, for example, of the Pelican-Bismarck vein system, one of the strongest and most productive systems of the district. The ores of this vein system carry blende and galena with some

pyrite, with a principally quartz gangue, usually subordinate in amount to the metallic minerals; and occur in shoots impregnating and replacing to a greater or less degree the crushed zone which accompanies the fault-slip (Fig. 18).[14]

Nevertheless, there are some striking and important cases where the same type of ores has indubitably been deposited

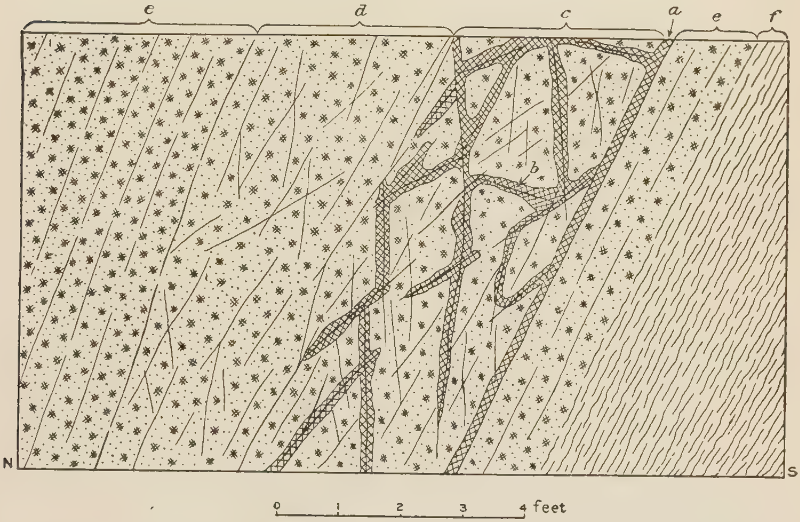

FIG. 18.—Fissure vein originating by replacement, along minor slip planes, of crushed fault material, by aqueous ore solutions. Cross-section of Pelican vein, Georgetown district, Colorado. *a,* Main lead; *b,* ore, chiefly blende; *c,* ore zone of brecciated, highly silicified alaskite porphyry; *e,* sheeted silicified alaskite porphyry; *f,* altered grantic gneiss. From J. E. Spurr and G. H. Garrey: Professional Paper 63, U. S. Geol. Surv.; Fig. 36.

in fissures; and some of the features of these fissure fillings have remained in the background of my mind as not satisfactorily accounted for ever since I studied the district.

The Terrible group of veins embraces the strongest lodes in the Georgetown district; they are, in the main, well-defined fissure veins, following strong fracture zones or filling fissures once open. Large quantities of coarsely crystalline dark-colored blende are characteristic of the Terrible

[14] *Professional Paper* 63, U. S. Geol. Surv., Fig. 36, p. 189.

lodes, with typically little visible gangue, of quartz or otherwise. The other common metallic minerals are galena and pyrite, with some chalcopyrite. The ore carries an average of 25 to 30 ounces of silver, and a very small quantity of gold.

FIG. 19.—Horizontal section of locality on Mendota vein, Georgetown district, Colorado. Shows deposition of blende by impregnation of gouge zone. *a*, Hanging-wall slip; *b*, foot-wall slip; *c*, zone of gouge or crushed rock (black markings are ore, chiefly blende); *d*, hard black gneiss (wall rock). Spurr and Garrey: Professional Paper 63, U. S. Geol. Surv.; Fig. 68.

The veins evidently are the filling of fissures, which were opened for a distance of hundreds of feet horizontally and vertically. The Mendota vein is characteristic of the group, and its description may serve for all. In places this lode shows only slip walls, with no mineralization. This tight slip opens up abruptly to a strong vein one to four feet wide, filled by blende (with pyrite), inclosing numerous angular fragments of the wall rock. On the Victoria tunnel level, for

example, this vein shows for several hundred feet the type of strong vein described; then it narrows, and the continuation is a zone of fractures marked by small seams of blende. Farther on, the vein-slip becomes poor, and is not mineralized; still farther, it becomes stronger and wider, and, although not generally mineralized, contains bunches of galena, pyrite, and blende, up to a few inches in diameter (Fig. 19). Beyond this the vein opens up, and within a short distance becomes a solid blende vein 2½ feet thick, inclosing angular fragments of the country rock (wall rock).

Two circumstances show that these last-named strong portions of the veins actually occupied open fissures, and were not by any chance formed by replacement. First, they contain numerous angular fragments of the wall rock, which are neither rounded, corroded nor replaced; second, they are generally lined, between the walls and the blende, with a thin band of comb quartz, the crystals of which are perpendicular to the walls and prove that they were deposited after the cavity was open, and before the deposition of the sulphides, which are practically free from admixture of intercrystallized quartz or other gangue.

We cannot avoid this conclusion, although from local data, as well as general knowledge and observation, we know that this is not a superficial type of vein—on the contrary, it is a fairly deep-seated type. Mr. Ball calculated that the amount of rock stripped from this district by erosion since the intrusion of the dikes which accompany the veins was at least 4,250 feet, and might be 5,250 feet or more.[15] The veins, moreover, have a great vertical range, some of them having been developed by mine workings for at least 1,800 feet below their surface outcrop; therefore the depth of mineralization can be generalized at several thousand feet.

Now, I had in mind at the time of my examination of this district, the conception (which I think I shared with all other geologists) that the solutions which deposited

[15] *Professional Paper* 63, U. S. Geol. Surv., p. 145.

these sulphides could be no other than waters bearing relatively small quantities of sulphides in solution, and that the sulphides were gradually precipitated from vast quantities of these solutions moving through the fissures. Reflection, however, has convinced me that this is not so. There is no banding or crustification whatever in these sulphide veins, as there must have been had the veins been deposited gradually from solution. I can hardly avoid the conclusion that the veins were filled all at once, as if a solution "froze" into metallic sulphides.

Another still more important feature of these veins should be described. I noted above that the fissure veins of the Mendota type contained many angular inclusions of the country rock, uncorroded and with clean demarcation from the ore. This was a most puzzling and striking phenomenon, being like the clean angular inclusions which one finds in an igneous intrusive rock. Having always in mind the conception of water as the mineralizing agent, there was only one explanation, which I adopted—namely, that subsequent to the opening of the fissure, it became filled with angular fragments, which had broken away from the wall, and which, resting lightly on one another by their sharp edges, left large cavities between, which were filled by the ore deposition. The circumstance that in ore exposures these angular inclusions did not come in contact with one another troubled me greatly, and could be explained only by the supposition that the points of contact and original mutual support of the blocks were either in front of or behind the section available. The situation is shown in Fig. 20, sketched at the time of examination.[16]

I now feel obliged to abandon the explanation which I then adopted, and to consider that my own sketches (which I carefully made underground at that time) preclude this theory. Take Fig. 20, for example, showing the Mendota vein at one point in the roof of the Victoria tunnel: note that the blende area is relatively too large as compared

[16] *Professional Paper* 63, U. S. Geol. Surv., p. 231, Fig. 70.

with the area occupied by the included granite blocks to harmonize with the explanation of the rubble-filled fissure; that *no two of the inclusions touch each other, and that none of the inclusions touch the wall rock.* Here, then, if the sketch is accurate (and I think that it is) is a very remarkable cross-section for a rubble-filled fissure. But let us consider the other sketches I made and published. Consider Fig. 21.[17] This shows the same vein in the roof of the same tunnel, at another point. All the observations

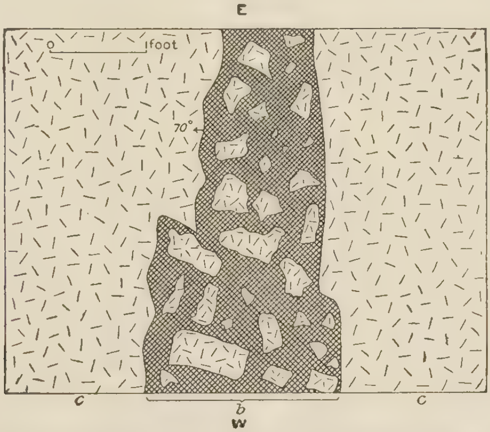

FIG. 20.—Horizontal section of portion of Mendota vein, Georgetown district, Colorado. Shows isolated inclusions of granite in solid blende, and illustrates intrusive concentrated ore magma. *b*, Blende; *c*, granite. Spurr and Garrey: Professional Paper 63, U. S. Geol. Surv.; Fig. 70.

regarding the previous sketch apply here also, and in addition all the inclusions are confined to one side of the vein—the foot-wall side. The difficulty of visualizing this as a rubble-filled fissure becomes greater, unless we grasp at the last possibility that each of these blocks may have rested at some point on the foot wall, in spite of the fact that none of them show such contact in the section. But we cannot hold this: the vein is nearly vertical, dipping 83° on the average. This impossibility is further shown by Fig. 22[18] a vertical cross-section of the Phillips vein, belong-

[17] *Professional Paper* 63, U. S. Geol. Surv., p. 231, Fig. 69.
[18] *Op. cit.*, Fig. 72.

ing to this system, and a neighbor of the Mendota vein, in the same workings. Here we have the same phenomena, including the restriction of the chief inclusions to the foot-wall side of the vein, the dip of which is so steep as to preclude

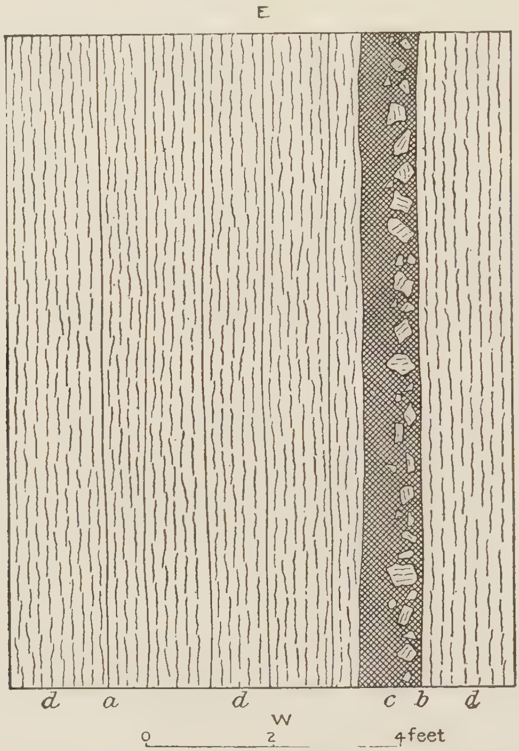

FIG. 21.—Horizontal section of portion of Mendota vein, Georgetown district, Colorado. Shows isolated inclusions of country rock in solid sulphide vein, and illustrates intrusive concentrated ore magma. Note settling of inclusions toward nearly vertical foot wall. *a*, Hanging-wall slip; *b*, foot-wall slip; *c*, zone of coarse blende, pyrite, and galena, containing angular fragments of gneiss; *d*, hard black gneiss (country rock). Spurr and Garrey: Professional Paper 63, U. S. Geol. Surv.; Fig. 69.

any possibility of the blocks resting in an open fissure in their present position. This is an especially interesting occurrence, for the hanging wall and the foot wall are of different rocks, on account of the faulting which produced the orig-

inal vein fissure, the hanging wall being gneiss (hard and black) and the foot wall granite.

In Fig. 20, both walls are granite, and so are all the inclusions; and in Fig. 21 both walls are in the hard black gneiss, which also constitutes all the inclusions. Now, in this last Fig. 22, from the Phillips vein, all the fragments shown in the sketch are from the gneiss hanging-wall rock. Their position in the foot-wall section of the vein indicates that gravity has had a part in bringing them there, but surely a very slight part; for it is indicated with what approaches convincing clearness, not only by this last drawing but by all the others, that these fragments were

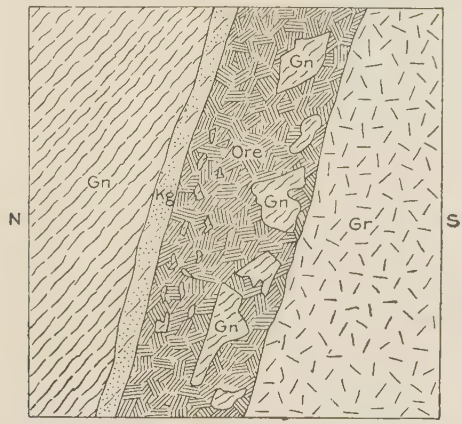

Fig. 22.—Cross-section of portion of Phillips vein, Georgetown district, Colorado. Shows isolated inclusions of hanging-wall rock in solid sulphide vein. Illustrates intrusive concentrated ore magma. Note that fragments of gneiss from hanging wall have settled toward the foot wall. Orientation of inclusions indicates pressure from walls at time of consolidation of veindike. Gn., Gneiss; Gr., granite; Kg., kaolinized gneiss and gangue. Spurr and Garrey: Professional Paper 63, U. S. Geol. Surv.; Fig. 72.

held in suspension in the vein solutions which deposited the sulphides, in much the same way as the inclusions are held in the liquid magma of ordinary intrusive rocks like granites or porphyries: in other words, that the ore-bearing solutions were heavy or thick solutions.

It will be noted in Fig. 20, which is, it may be repeated, a horizontal section shown in the roof, that there is no limitation of the granite blocks to either side of the vein, in contrast with the migration of the gneiss blocks in Figs. 21 and 22 to the foot-wall section. From this we might be inclined to argue that the specific gravity of the solutions was about the same as that of the granite and slightly less than that of the gneiss.[19] Mr. Ball records that a specimen of the black biotite schist from this formation (I do not know from what point in the quadrangle) was determined by Mr. Waldemar Schaller as having a specific gravity of 2.737. The specific gravity of this granite, or even of any granite in the quadrangle, has not been determined, but in general the specific gravity of granite is about 2.65. The specific gravity of blende is 3.9 to 4.2, of galena 7.25 to 7.7, of pyrite 4.83 to 5.2. If we hazard a guess at the composition of these particular veins figured as 70 per cent blende, 15 per cent galena, and 15 per cent pyrite, we shall have an average specific gravity (disregarding possible small amounts of gangue) of about 4.67. If this combination was deposited from a solution with a specific gravity of 2.65, it will be seen that the sulphides made up slightly less than half of the solutions, on the assumption that the balance was water. This is an entirely different type of solution from that which we have been accustomed

FIG. 23.—Fissure vein of highly argentiferous smaltite and calcite in diabase. Photograph by W. L. Whitehead, Econ. Geol., Vol. XV, No. 2, March, 1920; Plate VII. Some of the angular diabase fragments included in the vein are entirely isolated and unsupported. What held them thus, in the ore-magma-solution filled fissure? Width of vein at top of sketch, about five inches.

[19] There are other factors to this problem, however, to be discussed later.

to conceive, and one with which we have no acquaintance. A blende solution such as this is not so very far removed from the pasty intrusive blende of the Mandy. Yet the blende of the Terrible group of veins was not pasty, nor did it flow after crystallization set in; and the coarseness of the crystallization also shows the liquidity of the solution or magma. Had some accident, such as compression of the walls, or some strong upward urge from below, put it in movement at the time that crystallization set in, we would have had a pasty flow-streaked mass like that of the Mandy, which would have been intrusive into newly opened fissures.[20]

Are these fissure veins of the Terrible or Mendota type, then, to be regarded as still belonging to the series of "veindikes" which we have been considering, or are they simply "veins"? They have crystallized in place from solution, but so, as a rule, have igneous dikes, as well as the pegmatite and pegmatitic quartz veindikes. Have these heavy solutions acted as an intrusive magma, or was the

[20] Angular fragments of wall rock included in vein material are also shown in the accompanying illustration (Fig. 23) from Cobalt, Ontario (W. L. Whitehead: "The Veins of Cobalt, Ontario," *Economic Geology*, March, 1920. Plate VII-A). This is a four- to six-inch vein of smaltite (arsenide of cobalt), rich in silver, and of calcite, cutting diabase. The author (Dr. Whitehead) gives this as an illustration of "unsupported fragments," pointing out that the fragments are unsupported by the walls. He, therefore, concludes that the vein did not fill an open fissure, but originated by replacement, inferring that these fragments are residuals untouched by the replacement process. Study of the photograph from which this figure was traced does not give much faith in this explanation. If these fragments of diabase in the vein are residuals from a replacement process, how shall we explain the sharp outlines, and above all the long sharp angular corners? Would not any process of replacement or absorption have attacked such salients, and reduced them, so that the fragments would have been more rounded? To me they appear true inclusions, and I incline again to the explanation that the intrusive vein magma which split open the rock and forced its way in was heavy enough, or viscous enough, or congealed quickly enough, to hold these diabase fragments in suspension. We do not know the specific gravity of the Cobalt diabase, but in general the specific gravity of diabase varies from 2.7 to 2.9 and over; so that if the solution were heavier, it was 2.8 or over.

magma solution lacking in intrusive force, simply possessing sufficient force to rise into fissures already prepared for it? In one respect, at least, it resembled a veindike magma—it arrived, a concentrated sulphide solution, at a definite epoch, after the intrusion of porphyry dikes (and therefore welling up as a magmatic differentiation from the magma-laboratory which sent forth the porphyry), and the

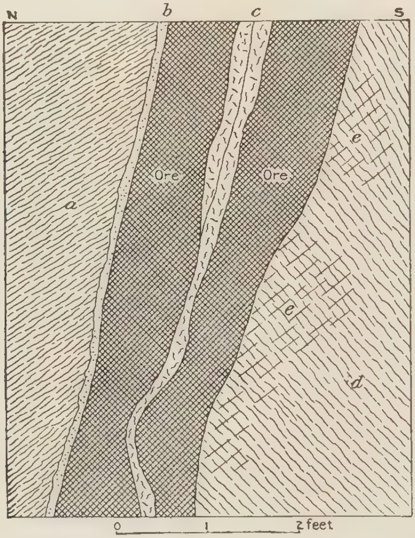

FIG. 24.—Cross-section of portion of Phillips vein, Georgetown district, Colorado. Shows slab of gneiss midway in solid sulphide vein. Illustrates intrusive concentrated sulphide magma. *a*, Micaceous gneiss; *b*, gouge selvage (ground-up rock); *c*, mixture of quartz and crushed silicified gneiss; *d*, hornblende gneiss; *e*, fractured gneiss. Spurr and Garrey: Professional Paper 63, U. S. Geol. Surv.; Fig. 73.

surge was not repeated, for the next solutions were of a different character.

Several instances show the blende veins (containing some contemporaneous galena and pyrite, and so showing their kinship to and continuity with the subsequent veins) split open by later movements, and the resulting fissure filled by massive crystalline galena in some cases, and by massive pyrite in others; and of these two, the pyrite seems the

later. That the vein solution may have exerted intrusive pressure and locally widened the fissures or crevices which it found, to make room for itself, is indicated by the phenomena of angular inclusions, which suggest that these blocks broke off in the intrusion process; also, rather more clearly by an occurrence like that shown in Fig. 24,[21] where a thin continuous strip of gneiss in the middle of the massive sulphide vein can hardly be conceived as occupying this position in a pre-existing open fissure; while the very fact that it is there precludes the idea of an origin of the ore by replacement. It must have been held in place, in its precarious position, by the pressure of the ore-magma solution; and this pressure we may believe to have been the same as that which enabled intrusion.[22]

We must conclude that this section, shown in Fig. 24, represents an intrusive veindike, and it is probable that many other portions of the fissure veins have the same origin.

Further interesting data on the problem of the manner of vein formation were observed in the Griffith mine,[23] three or four miles east of the Mendota. Here there have been two distinct general periods of fissuring and subsequent vein formation. The first formation was a nearly pure sulphide vein, which filled an open fissure, and in which

[21] *Professional Paper* 63, U. S. Geol. Surv., Fig. 73.

[22] Specifically, I shall argue later that this pressure, allowing intrusion, is a gaseous-tension pressure. We have, apparently, several factors which allowed inclusions to remain isolated and unsupported, up to the time of the freezing of ore-magma solutions, besides that of great concentration and therefore high specific gravity: there is also the factor of jelly-like physical condition, which in certain stages impedes the settling of inclusions; and there is the gaseous tension of the ore-magma solution. Of course, gravity would tend to cause inclusions heavier than the ore-magma solution to settle, in spite of the gaseous-tension pressure, or a jelly-like physical condition; but in the case of intruding solutions, the upward pressure may sometimes have been greater than that in other directions, and may have impeded or neutralized the gravity settling; or there may have been an actual upward current. A quick freezing of the ore-magma solution directly after intrusion is also frequently indicated.

[23] *Professional Paper* 63, U. S. Geol. Surv., p. 285.

angular fragments of the wall rock are embedded; this is altogether of the Mendota type just described. As in the case of the Mendota, the first deposition in the fissures was a thin lining of comb quartz, after which the bulk of the fissure was filled by coarsely crystalline galena, blende, pyrite, and chalcopyrite, with practically no intermixed gangue. Subsequent to this, there was a splitting open of the vein, following the line of the old fissure, and a fissure vein of quite different type, but of larger dimensions than the first vein, was introduced. In general, the new vein followed the line of the old one, which it split and shattered. In many places it split the old vein in the middle, leaving a band of sulphides clinging to each wall; in other places the new vein runs distinct from and parallel to the old one, with a zone of wall rock between; and in still other cases a vein of the new period runs transversely across the old vein. The vein filling of the second period consists principally of pyrite and brown carbonates of iron, manganese, and magnesia, with more or less quartz (occasionally predominant) and a very little galena, blende, chalcopyrite, and barite. The values in the first-period vein material are principally lead, with some silver; the second-period vein material carries some gold and silver, but is of low grade.[24]

The carbonates of the second period are not coarsely crystalline; they form a dense granular aggregate, in which pyrite has also crystallized.

At the time of our examination and report I explained the angular inclusions of sulphides from the first-period vein, in the later vein material, as due to these fragments having fallen into the fissure opened after the first vein deposition and having there lodged in some way until the deposition (from thin solutions, as I supposed) of the carbonate-pyrite filling. As in the case of the Mendota vein type, I am unable now to fit the facts to this explanation.

[24] Ten to 12 ounces silver, and $2 to $3 in gold per ton.

Fig. 25[25] is a careful drawing made of a specimen of the vein (showing both vein periods) which I had polished for the purpose. I afterward kept this specimen for years on my desk as a paper weight. The study of it fascinated me,

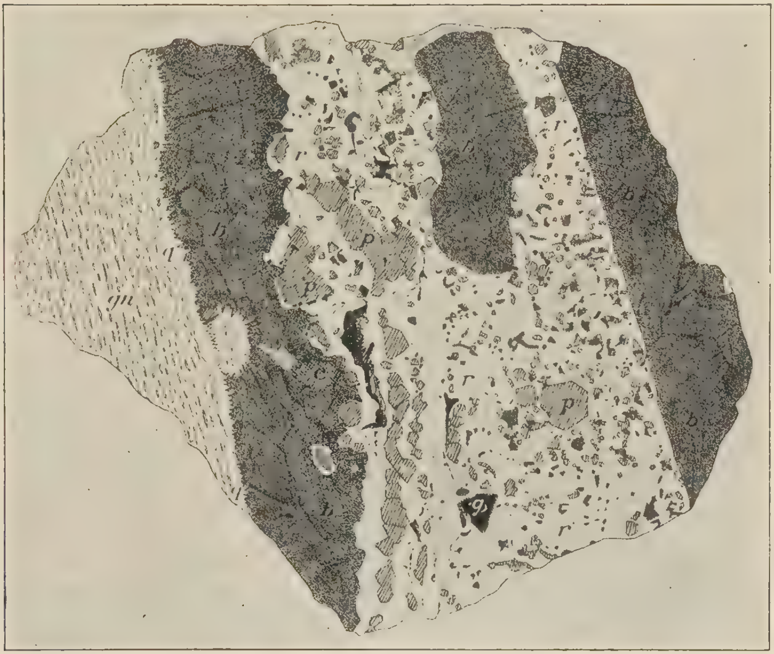

FIG. 25.—Drawing, natural size, of specimen from Griffith mine, Georgetown district, Colorado, showing a solid sulphide fissure vein which has been split open and the new fissure filled with manganese-iron carbonates (*r*) and pyrite. Illustrates two periods of intrusive concentrated ore magmas. Note isolated inclusions of sulphide ores in carbonate-pyrite veindike. *gn*, Gneiss wall rock; *q*, quartz (comb structure); *b*, blende; *p*, pyrite; *c*, chalcopyrite; *g*, galena. Spurr and Garrey: Professional Paper 63, U. S. Geol. Surv.; Plate XV.

and it was finally borne into my mind that the carbonate-pyrite material must have been introduced, not as a highly aqueous solution, but essentially as fluid carbonates. Note the angular fragments of blende and of galena embedded in the carbonate-pyrite matrix: the galena has had a thin fringe of pyrite precipitated on it.

[25] *Professional Paper* 63, U. S. Geol. Surv., Plate XV. A.

The specific gravity of both galena and blende is heavier than that of this carbonate-pyrite mixture, so no solution of this mixture could be heavy enough to long support these fragments, which by no chance could have had points of contact and support, with one another or with the wall rock. I can conceive of no adequate explanation other than that the vein material of the second period was intruded in

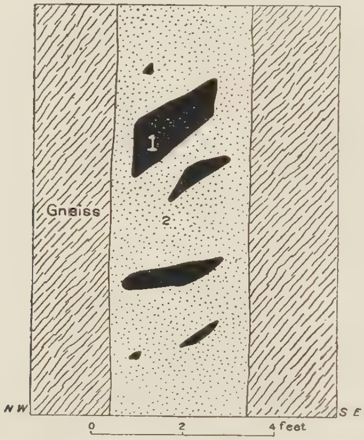

FIG. 26.—Vertical sketch section of portion of Griffith vein, Georgetown district, Colorado. Shows intrusive carbonate-pyrite veindike (2), containing isolated and unsupported broken fragments of galena which belongs to an earlier (sulphide magma) intrusion (1). Note that flow of carbonate-pyrite magma has borne the sulphide fragments with it from some other locality. Note that fragments are of greater specific gravity than matrix. Note the orientation of fragments, indicating resistance, at time of consolidation of matrix, either to an upward flow, or to gravity settling. Spurr and Garrey: Professional Paper 63, U. S. Geol. Surv.; Fig. 107.

a gelatinous state, in a condition between solution and crystallization (indeed, in nearly the exact state in which I conceive the Mandy blende and chalcopyrite ores to have been intruded); and that the fragments of heavier ore, broken off, were held in suspension in this gelatinous mass.

A student of this specimen might perhaps suspect that the large isolated mass of blende in the upper right-hand corner of the drawing had been split off from the blende

which forms the right-hand wall of the carbonate-pyrite vein, by the force of crystallization of the latter; but he can hardly entertain this for the small triangular fragment of galena in the lower portion; and any doubt as to the true conditions is in my mind at once dispelled by Fig. 26,[26]

FIG. 27.—Sketch of specimen from Griffith vein, showing same two periods of veindike ore-magma intrusion as in Figs. 25 and 26; and here especially an initial banded structure for the second-period carbonate-pyrite magma. *a*, Included fragments of galena, belonging to first period; *b*, banded carbonates; *c*, quartz with sulphides; *d*, brown carbonates and quartz, containing some pyrite *(e)*. The phases *b, c,* and *d* are all differentiates, by successive deposition on the fissure walls, of the ore magma of the second period. Spurr and Garrey: Professional Paper 63, U. S. Geol. Surv.; Fig. 105.

which is a sketch of a vertical exposure of the vein at another point in the Griffith mine. Here large angular galena fragments of the first-period vein have been torn off and carried into a new fissure with the carbonate-pyrite magma. Note the parallel orientation—with their long axes approximately horizontal—of the included fragments, evidently

[26] *Professional Paper* 63, U. S. Geol. Surv., Fig. 107.

assumed as offering the maximum resistance to the upward pressure of the carbonate-pyrite paste or the settling in it. Yet this carbonate-pyrite magma shows no flow structure (unlike the Mandy ore), and therefore did not flow after definite crystallization set in.[27]

Rarely there is evidence of a brief period of more gradual deposition of these carbonates, on the walls of the fissure which resulted from the splitting open of the original sulphide vein. A specimen sketched[28] (Fig. 27) shows on galena fragments a finely banded carbonate deposit less

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[27] In the gold-quartz veins at Bendigo, in Australia, F. L. Stillwell (*Econ. Geol.,* Vol. XVI, March, 1921) has remarked that there are many large and small inclusions of the country rock, which are not in any way supported by the walls.

Lindgren (*Econ. Geol.,* June, 1920, p. 312) describes a specimen from the Bendigo mines, where an irregular quartz bleb or veinlet in shale is bordered by earlier ankerite. Lindgren believes that this signifies that the cavity was there before the quartz was deposited, whereas he notes that Messrs. Taber and Dunn ascribe the opening of the veins to the pressure of the crystallizing quartz. I am inclined to think that the opening was produced by the intrusive pressure of the vein magma and that the first precipitate from this magma, along the walls of the cavity, was ankerite, after which the residual quartz "froze" in the bulk of the veinlet, a conclusion similar to that arrived at in the case of the Griffith vein. Some of the shale inclusions in the figure (Fig. 28) seem to warrant the same conclusion as to a viscous vein magma capable of holding inclusions in suspension, as in the case of the Griffith.

Isolated fragments of slate wall rock in a California gold-quartz vein are shown in the accompanying figures from Lindgren (Fig. 29). The fragments have been altered largely to calcite and siderite; subsequently, arsenopyrite has been deposited around the veins and also to a greater or less extent in the interior of the fragments. Still later, pyrite has been deposited around the rims. These rim depositions of sulphides show that the fragments were isolated, and in their present form, during the sulphide deposition; and the sulphide deposition evidently preceded the quartz deposition, for the latter is practically free from sulphides. The original beautiful illustration, to which I refer the reader, as it cannot well be reproduced, shows all these details. No explanation will fit this case except that the fragments were held isolated and more or less at rest in a liquid siliceous ore magma from which were deposited in and on the fragments successively: (1) calcite and siderite; (2) arsenopyrite; (3) pyrite. The magma then "froze" as quartz.

[28] *Professional Paper* 63, U. S. Geol. Surv., Fig. 105, p. 288.

than half an inch thick, which was followed by a very thin crust of quartz with some sulphides; and following this the main fine massive carbonate-pyrite material, containing also quartz, filled the fissure. The banded carbonate and the quartz was plainly a deposition or precipitate from solutions which were similar in composition and closely allied to the pasty mass that crystallized subsequently, and were therefore probably not thin, but highly concentrated, like the solutions which deposited the sulphides of the first-period vein. The banded deposition took place by precipitation

FIG. 28.—Quartz from the Bendigo district, Australia. See text. After Waldemar Lindgren: "Econ. Geol."; Vol. XV, Plate X.

on the cooler wall rock when the solutions as a whole were still fluid: as they "froze" they formed the main mass of later vein filling.

This occurrence indicates that fine crustified or banded veins may be deposited from thick saturated solutions, distending a fissure, and not necessarily in process of flowing; and, conversely, that banding or crustification is no proof of circulating thin solutions.

In this case again I see no reason for believing that the nature of the carbonate-pyrite vein magma was necessarily an extraordinary one, or that it may not furnish a clew as to the nature of the solutions which have deposited similar

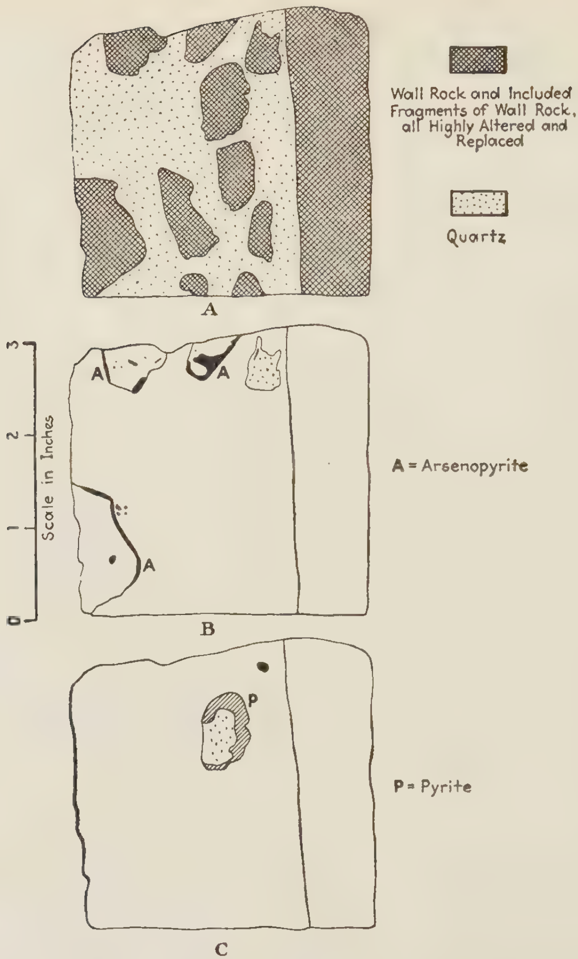

Fig. 29.—A. Drawing of portion of Federal Loan auriferous quartz vein, Banner Hill district, California. Natural size. After W. Lindgren: 17th Ann. Rep. U. S. Geol. Surv.; Part II, Plate VII b. Shows "including fragments of black argillite altered to yellowish gray calcite-sericite rock, with arsenopyrite, and surrounded by pyrite." The accompanying drawing is a simplified reproduction of Lindgren's plate.

B, Same as A. Detail of some of the included fragments, showing deposition of arsenopyrite (A) on the margins of fragments, which had previously been largely replaced by carbonates.

C, Same as A. Detail of one of the included fragments, showing deposition of pyrite (P) on margin of fragment which had previously been partly replaced by arsenopyrite.

material elsewhere (See Chapter XVIII). This mixture of brown carbonates of iron, manganese, magnesium, etc., is one frequently found in ore deposits, occurring as a distinct stage in the sequence of definite stages of deposition of different vein materials, which we can decipher in nearly every ore deposit.

The proportion of water in these vein-forming solutions is thus shown not necessarily to be greater than in peg-

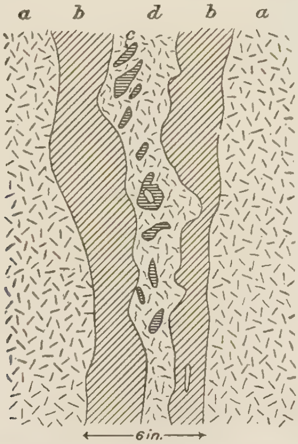

Fig. 30.—Section of banded pegmatite veindike, Georgetown, Colorado, in granite *(a)*. Shows feldspar *(b)* on walls, and quartz *(d)* containing biotite *(c)* in center. The feldspar and quartz-biotite bandings are successive differentiates, crystallized from the fissure walls outward, from the pegmatite magma-solution. Drawing by S. H. Ball: Professional Paper 63. U. S. Geol. Surv.; Fig. 17.

matites. Pegmatites not rarely show a zonal or banded arrangement, due to an earlier deposition of certain minerals nearer the walls and a predominance of another mineral in the center. This is frequently shown in the case of quartz-feldspar pegmatite veindikes, where the feldspar is zoned along the side with the quartz in the middle. Mr. Ball has noted and sketched such a definitely banded pegmatite veindike near Georgetown,[29] (Fig. 30), with feldspar deposited next the walls of the fissure and quartz with

[29] *Professional Paper* 63, U. S. Geol. Surv., p. 63.

biotite in the center; and I have recorded and sketched a very narrow and regular pegmatite veindike in granite, only an inch wide, also near Georgetown,[30] (Fig. 31), which

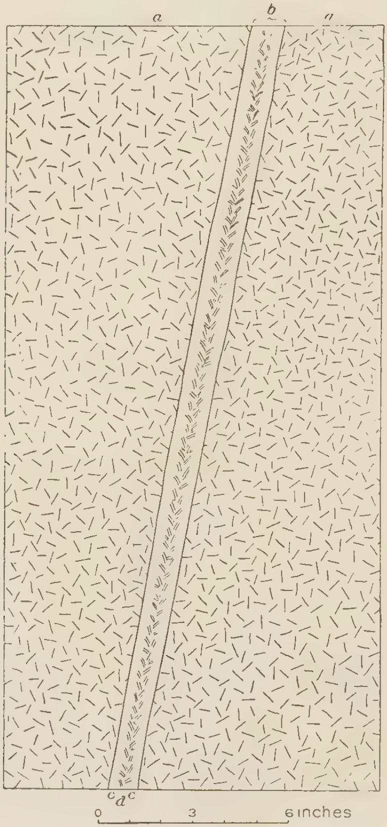

Fig. 31.—Section of pegmatite veindike (*b*) in granite (*a*), Georgetown, Colorado, with quartz (*c*) on the sides and muscovite (*d*) in the center. The quartz and muscovite bandings are successive differentiates on the fissure walls from the pegmatite magma-solution. Drawing by Spurr and Garrey: Professional Paper 63, U. S. Geol. Surv.; Fig. 32.

shows pure quartz on the sides and solid muscovite in the center. It is surely not remarkable that opinion was so long divided as to whether pegmatites were dikes or veins.

The conclusion as to the ore deposition in these veins

[30] *Professional Paper* 63, U. S. Geol. Surv., p. 183.

being a definite injection of highly concentrated solutions is in accord with other conditions. The fact that the veins formed after the dikes in the Georgetown district and in many cases ascended along the same fissures which were

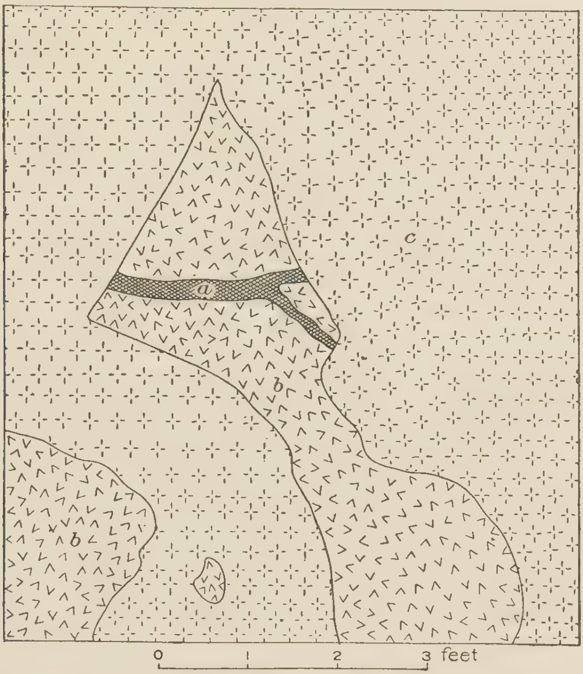

Fig. 32.—Idaho Springs, Colorado. Stanley mine. Later dike, intrusive along an earlier sulphide fissure vein. Drawing shows relative ages. *a*, Galena-pyrite ore, intruded into pegmatite *(b)*. Both have been broken and caught up in the dike rock (latite, *c*).

followed by the dikes (these fissures being rent open again) indicates their being a phase of igneous action; and the occurrence at the Stanley[31] mine, where the vein[32] was formed along a fissure which was followed, both earlier and later than the vein formation, by dikes belonging to the same general period of intrusion, shows that the stage of

[31] *Professional Paper* 63, U. S. Geol. Surv., p. 342.

[32] The Stanley vein consists of quartz and pyrite, with considerable galena and chalcopyrite.

vein formation represented a point rather than a range of geologic time, and was in so far comparable to the intrusion of a dike (Fig. 32). This is a conclusion which I have abundantly proven in many other districts.

At Aspen, also in Colorado, ores which are connected with the intrusions of the same general monzonitic magma as the silver-bearing lead-zinc veins of Georgetown, which correspond in general character to these ores, and are considered to represent the same type of ore deposition, were formed in a region of profound faulting; and while the faulting occupied a relatively long period of time, the ore deposition took place at a certain brief stage, earlier than some of these faults and later than others.[33] A similar definite brief period of vein formation is demonstrated in many other districts which I have studied.[34]

It may be worth while to consider for a moment, in passing, the lessons as to the origin of mineral veins which are taught us by an occurrence like that of the Stanley vein, which is evidently a fair type. Such an occurrence plainly shows that vein deposition is not due to any cause which acts everywhere and at all times—it disposes at once of all uniformitarian theories. Such a vein has not been deposited by ordinary ground waters, whether descending, ascending, or laterally moving, which have leached their metallic contents from the rocks they have traversed. After the last dike filling, the fissure was reopened, and it has been the channel for circulating ground waters ever since; but there has been no further deposition.

The theory that mineral veins are associated with eruptive rocks because ground waters, coming into the region of such rocks before they were cooled, became heated and therefore potent in dissolving out the disseminated minerals found in the rocks, and so were able to form veins by deposition on ascending into a cooler upper zone, is also untenable. After the second dike and the reopened fissure

[33] *Econ. Geol.*, Vol. IV, 1909, p. 301.
[34] *Op. cit.*, Vol. XI, No. 7, 1916, p. 601, etc.

which succeeded it, we should have had a new vein by this theory; but we have none. Moreover, there are at Idaho Springs, only a few miles away, abundant hot springs, which doubtless derive their heat from igneous rock at depth, so that this whole district has certainly been open to ascending hot waters since the vein deposition, for extensive post-vein fissuring is one of the characteristic features of the district; yet while the rocks along these later fissures have been somewhat indurated, they are not mineralized.

It is interesting to observe how many theories weaken and collapse at the touch of facts, if one is so rude as to bring the two together; also that many such views built with a rather larger proportion of imagination than is properly allowable except for a working hypothesis (for without some imagination we should not be able to detect geological truths at all) are held to be "conservative," since they are constructed upon the analogy of processes which we have seen with our own eyes.

It is with a certain sense of humor that I survey my own "pilgrim's progress" in seeking the truth about ore deposits, for the reader must by no means look to find my present views as I state them here, in all my published reports on various districts. Let me reflect, for example, on my report on the ores of Monte Cristo, Washington,[35] where in veins in intrusive tonalite or granodiorite of Middle Tertiary age I found that the upper zone of the veins, near the surface, was characterized by galena, blende, and chalcopyrite, with some arsenopyrite and pyrite, and carried pay values in gold and silver; while in depth the leaner ores consisted chiefly of arsenopyrite and pyrite, poor in the precious metals, and with very little galena, blende, or chalcopyrite. In the upper and richer surface zone there was a definite zonal arrangement to be observed, galena being uppermost, blende next, and chalcopyrite lowest. The conclusion was reached on various grounds that[36] "the ores of the upper

[35] *Twenty-second Ann. Rep.*, U. S. Geol. Surv., Part II, p. 844.
[36] *Op. cit.*, p. 851.

sulphide zone were formed by surface waters within the general period of the present climate and topography." As to the origin of the leaner lower sulphide zone, I found little evidence, but accepted the hypothesis that it had the same origin as the upper zones—namely, that it had been deposited by waters descending from the surface: and this involved the explanation of the derivation of the ores by leaching of disseminated metals from the intrusive tonalite or granodiorite.

Also, concerning my first report on the Aspen district, in Colorado. At Aspen I held[37] that the ores, which are principally argentiferous galena and blende, mainly replacing limestone or dolomite along fault fissures, and evidently connected with intrusive igneous rocks, were deposited by hot ascending solutions or hot-spring waters; that these waters were derived from the surface, and in sinking came in contact with a body of heated igneous rock, and so gained heat and dissolved metallic and earthy materials from the rocks, which materials were deposited as ores, on the subsequent upward journey of the waters along fissures.

In the ores of the Georgetown quadrangle, also (which I have just been discussing), I reached the conclusion that fissures formed subsequent to the intrusion of dike rocks became filled by hot ascending waters, similar to the hot spring now issuing at Idaho Springs, and that the veins were deposited from these; but reasoned that both the waters and the metals were emanations from the igneous magma in depth, and that the vein deposition was effected during a very brief period.[38]

I now am quite clear, as to Monte Cristo, that while my conclusions as to the origin of the richer sulphides in the upper zones of the vein were correct, yet the deeper zone of arsenopyrite, pyrite, and pyrrhotite, with a little galena, blende, and chalcopyrite, was derived from the depths below, subsequent to the intrusion of the tonalite or

[37] *Monograph* XXXI, U. S. Geol. Surv., p. 235.
[38] *Professional Paper* 63, U. S. Geol. Surv., pp. 146, 155, 156, 167.

granodiorite in and near which the veins lie. The wall rocks contain epidote, as a result of the alteration attendant upon vein formation, and the vein falls into the now familiar type which I have described above at the Great Gulch mine, in Nevada (p. 107), as formed at a certain stage of magmatic solutions—the type of the massive auriferous arsenopyrites. Since then I have seen in this same state of Washington, in the region just south of Mount Rainier, similar massive auriferous arsenopyrite veins, with tourmaline formed in the wall rock, an occurrence at once recalling what I have described at Herb Lake, in Manitoba.

Also, I now consider that the argentiferous galena-blende ores of Aspen are identical in type and origin with the similar ores of the Georgetown district, and that all have been deposited from highly concentrated metalliferous solutions originating by magmatic differentiation from an igneous magma; that this metalliferous magma was injected, at a certain definite stage of the differentiation process, into the overlying rocks, and formed fissure veins or veindikes, and also replacement and impregnation veins. I have already published notes as to my change of opinion concerning the origin of the Monte Cristo and the Aspen ores.

The patient scientific investigator studying a problem may circle around the truth he seeks in ever-narrowing circles, as new facts and experiences enable him to contract closer and closer the field of possibilities; but it is so far elusive in that, although he may indefinitely approach nearer, he can never arrive at a point where he can go no further. The spiral is infinite. It is one of the fascinations of science that it will always go forward, and never find an end to the road.

> "Flower in the crannied wall,
> I pluck you out of the crannies,
> I hold you here, root and all in my hand,
> Little flower, but if I could understand
> What you are, root and all, and all in all,
> I should know what God and man is."

I am beginning to realize that in seeking a conception as to the origin of vein-forming solutions, and in trying to correlate them with something with which we are familiar, we have been misled, not only by ordinary ground waters circulating in fissures, but by hot springs. Both certainly have some mineralizing activity, but neither, according to my conclusions, represent or at all resemble the vein-forming solutions I have described. In the case of hot springs we are circling nearer the facts; we are getting warmer, as the children say; but we apparently must dismiss them entirely from our minds and acknowledge them an unsubstantiated preconception before we can form a true mental picture.

Finally (for the present) I want to describe some interesting occurrences of veins at Tonopah, Nevada. Here we have veins formed at no great depth, in a late Tertiary volcanic complex of flows and intrusive sills. The first types and instances I have described (at Silver Peak, in the Yukon country, and in Manitoba) represented deep-seated veins in schist, associated with granitic intrusions; next, at Georgetown and other districts cited in Colorado, veins not so deep seated, but still formed under some thousands of feet of rock cover, and associated with intrusions of porphyritic dike rocks ("porphyries"). Tonopah is one of numerous representatives of the upper end of the vertical range; indications are that the veins were formed under a cover of not very many hundreds of feet.[39] The veins are of a complex type and they were formed at different periods.

Veins of the main period contain silver sulphides, chalcopyrite, and blende, with a gangue of quartz and adularia,[40] and are gold-bearing; those of a subsequent important period carry the same metallic and gangue minerals, and in addition abundant rhodochrosite. The pay values are all in silver and gold. There are also various stages of

[39] *Econ. Geol.*, Vol. X, p. 760.

[40] Potash feldspar: a crystalline habit of orthoclase.

barren or practically barren quartz veins (sometimes containing adularia).

The chief ore-bearing veins have formed mainly by replacement of crushed and sheeted fissure zones; but many of the veins of barren quartz have evidently not so formed, but are clean types of fissure veins, with no evidence of replacement, and with a sharp and clean line between vein and wall. Of such veins we are accustomed to think and say that they were deposited in open fissures, although I have already shown that the pre-existence of an open fissure before vein deposition is never probable, and in many cases plainly impossible; for in some cases the vein magma has evidently forced open the rocks dike-wise and made room for itself. This conclusion has been reasoned out for deep-seated veins, having a traceable relationship to pegmatitic injections, which notoriously have had this power to make their own way, and do not depend, like the hermit crab or the cuckoo, on having their nest prepared for them by some lucky accident: is it within the bounds of possibility that veins formed within a thousand feet, say, of the surface, can sometimes so originate?

One of the largest veins of the Tonopah district—thickest and most extensive—is the great MacNamara vein, which is flat, rolling and dipping at various usually gentle angles, and which evidently follows a flat fissure zone of great importance (Fig. 33). Usually it lies more or less along the contact of a trachytic flow[41] above and a later intrusive trachy-alaskitic sill[42] below; but where, on account of the irregularities of the intrusive sill, the underlying rock falls away sharply or is missing, the vein keeps on, with various other wall rocks above and below; it is of low-grade quartz, reaching up to 20 feet or more in thickness.[43] While quartz has intricately penetrated the wall rock, yet substantially the main vein bears the evidence of having filled a

[41] "Mizpah Trachyte." See Fig. 33.

[42] "West End Rhyolite." See Fig. 33.

[43] *Econ. Geol.*, Vol. X, No. 8, Dec., 1915, p. 736.

fissure, and little or none of having been formed by replacement. It is out of the question, of course, to suppose that a fissure of this width and extent was open to receive the

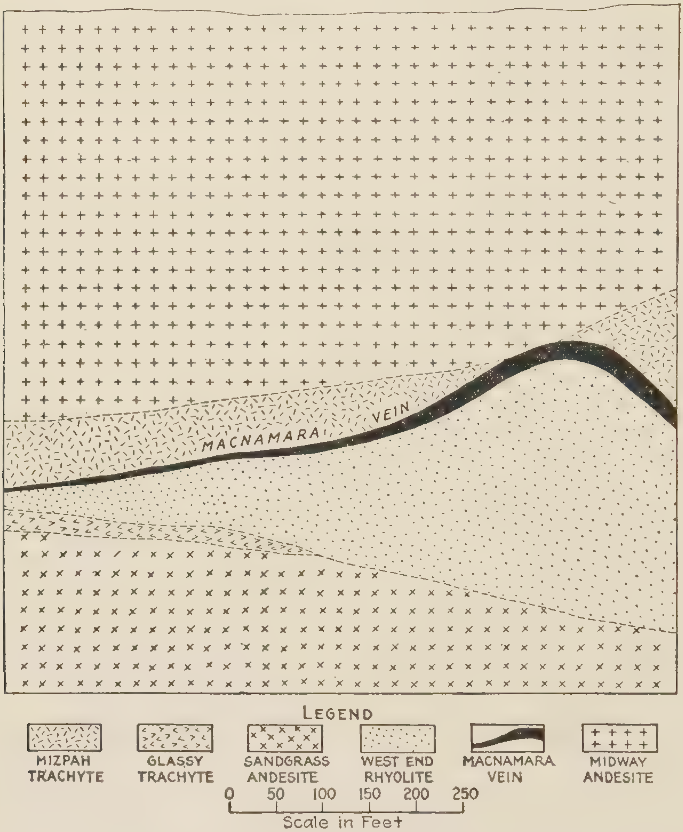

FIG. 33.—A vertical section through a portion of the MacNamara vein, Tonopah, Nevada; by J. E. Spurr. The different formations, in the order of relative age, are: 1, Mizpah trachyte and Glassy trachyte, the latter the basal marginal phase of the former; 2, Sandgrass andesite; 3, West End rhyolite; 4, MacNamara vein; 5, Midway andesite. All are intrusive except the Midway andesite, which is a surface flow.

quartz filling: such an opening would have offered no resistance to the direct weight of the overlying rocks. The only alternative seems to be that the opening was made by the siliceous vein material, which forced its way along this line

of weakness and fissuring (it is shown to have been an old line of flat faulting, repeatedly reopened by the intrusion of sills of andesite and rhyolite) under pressure sufficient to lift the overlying rocks and support them until the solutions crystallized into quartz.

At once I hear an outcry, How can "water" lift up and float a load of rock a thousand feet thick? For answer I ask another question: How could the liquid lavas of the sills above mentioned lift up this same load and hold it till they crystallized? While some of these sills are shown to have been of viscous lava, in process of congealing at the time of their intrusion, others—the andesite, for example—congealed and crystallized entirely after their intrusion, and must have flowed almost like water (or like any fluid surface lava) when injected. And even a viscous lava offers the same problem. Were it of the consistency of thick tar, would it offer substantially more resistance than water to the weight of a thousand feet of rocks resting on it? Be the intrusion as viscous as you please, what drove it in between the lava sheets? How does any liquid sill or intercalated sheet intrusive into stratified rocks (of which sills we see classic examples in Colorado, for example) sustain the immense weight of overlying strata, and how does it work itself into the position? This problem I will take up later: I merely wish to point out that there is no *a priori* reason why vein-forming solutions should not play the same intrusive rôle as igneous rocks: and that we have apparently in this case at Tonopah a vein so formed—a veindike, in short.

Therefore—as to the mode of formation of veins: Some vein-forming solutions, from the pegmatite solutions up through the range to those which have formed relatively near the surface, appear on occasions to be intrusive and form intrusive veins, or veindikes. Some vein-forming solutions also have the property of passing through the tiny openings and interstices of rocks, penetrating along crushed

and fractured zones, and replacing rocks so as to form replacement veins, and replacement and impregnation deposits of various form and extent, depending upon the nature of the rock traversed, and the nature of the fracturing.

CHAPTER III

The Secret of Igneous Intrusion

This chapter treats of the reason and method of intrusion of igneous rocks, of dikes and veindikes; of the formation of schistosity by flowage in rocks, due to the dynamic power of great igneous intrusions; of the formation of domical stratigraphic uplifts, due to the rise of magma domes or bosses in depth. The source of intrusive power is argued to be the gaseous tension of the magmas.

IN THE FOREGOING DISCUSSION of certain closely related dikes, veindikes, and veins, the deduction of forcible intrusion has been repeatedly made; and in each case I have gone no further, leaving the probing of the secret of igneous intrusion for a later discussion, and such explanation as we may have.

Let us forget for a moment the problem of the introduction of veindikes and veins and think only of dikes—dikes of granite, porphyry, or trap, for example. We are very familiar with these, frequently clean and regular, cleaving rocks of all types, igneous and sedimentary; we are also quite familiar with dike complexes, where one series of dikes after another cuts the older dikes.

How did they come in?

Following the formerly current theory as to the origin of veins, in that they filled pre-existing fissures, did the dikes do likewise? Did the older rocks yawn open, rent by volcanic convulsions, which squeezed the molten magma from below up into the fissures? We may dally for a moment with this theory for a small dike—say a dike an inch wide, or even a foot wide, or even a yard wide. Past this point we hesitate to go; but in the field the width of dikes does not hesitate at this limit of our credulity. Many cases can be noted in various igneous fields, where the size in different dikes increases to ten feet, twenty feet, a hundred yards, a

half mile. No, we must abandon the previous opening theory. There was none—the intrusions made their own way; they forced their passage, they cleft their entrance, driving or being driven like a wedge, with as stupendous an exhibition of physical power as I can conceive, parting the rocks to right and left and shoving them aside—pushing them back a foot, five feet, half a mile—and all this as easily, apparently, at depths of thousands of feet as near the surface. Here is a fluid—the typical dike has been injected or injects itself in a true fluid state—before whose pressure the solid crust of the earth recoils on itself and makes way for the soft but dynamic stranger as best it may.

It appears to be only within the last fifty years or so that the dynamics of igneous intrusion have begun to be even partly understood. The earlier geologists explained intercalations of sheets of igneous rock with sedimentary rocks as necessarily indicating an alternation of lava flows at the surface with periods of sedimentation. When, in 1877, Gilbert described the structure and mode of formation of certain intrusive dome-shaped bodies of igneous rock (which he called cistern rocks or laccoliths) in the Henry Mountains of Utah, it was a matter of astonishment to most geologists. In his monograph Gilbert showed how an igneous magma introduced through a fissure or other conduit into a thick mass of stratified beds in the Henry Mountains, instead of breaking through to the surface and forming a volcano, had spread out along a certain plane of stratification, and as it was fed by the magma from the conduit below, assumed the form of a dome, uplifting the overlying strata into an arch, while the base of the laccolith or cistern retained the usual contour, often nearly horizontal, of the stratification.

It was a matter of astonishment and even of disbelief to many geologists that a body of liquid magma should have uplifted a cover of several thousand feet of overlying strata. In explanation of this, Gilbert appealed to relative density, and considered that the movements of the igneous

magma were essentially governed by the laws of hydrostatic equilibrium,[1] and that the laccolith took its position in the stratified rocks in accordance with the relative specific gravities of the magma and the intruded rocks. "Given a series of strata of diverse and alternating density, a very light lava will traverse it to the top and be extruded, a heavier will intrude itself at some lower level, and a series of dissimilar lavas may select an equal number of distinct levels." In other words, the relative specific gravity of an igneous magma determined whether it should form a volcano or a laccolith. No intrusive potency within the magma itself was recognized; to use apt words, later employed, the magma migrations were conceived as "permissive" rather than "aggressive." Following this idea, certain lavas (with a certain range of composition) were supposed to be usually volcanic and certain others usually laccolithic.[2]

That laccolithic structures exist as described by Gilbert, not only in the Henry Mountains but elsewhere in the Rocky Mountain region, is now widely recognized; but his explanation of their origin has not been accepted. Cross[3] in 1894 described certain laccoliths in the Rocky Mountain region, corroborating similar descriptions by Gilbert, but came to the conclusion[4] that their intrusion and growth was not due to relative densities. He observes, "The facts above cited seem to demonstrate that the horizons occupied by intrusive magmas are not determined by 'relative densities of the intruding lavas and of the invaded strata,' and the question recurs as to what was the determining cause." Later he quotes J. D. Dana as follows: "*The origin of volcanic* heat, the *source* of *lava columns* beneath the volcano, the *cause of the ascensive force* in the lava column, are subjects on which science has various opinions and no positive knowledge."[5]

[1] "Geology of the Henry Mountains," U. S. Geol. Surv., 1880, p. 67.

[2] *Op. cit.*, p. 69.

[3] *Fourteenth Ann. Rep.*, U. S. Geol. Surv., Part II, p. 165.

[4] *Op. cit.*, p. 240.

[5] "Characteristics of Volcanoes," 1890, p. 24.

Existing opinions as to the origin of intrusive force still appear to be in a nebulous and highly speculative position. Iddings, for example, observed in opening the discussion on the subject in his book on volcanism[6]:

"Why do molten magmas shift their position and rise through the lithosphere? The occurrence of volcanic eruptions in regions of profound displacement . . . indicates that the fracturing of the brittle lithosphere, in adjusting itself to a shrinking core, was the occasion for the displacement of the potentially mobile, rigid magma zone beneath the frangible zone of rock." Here we have a false start, and a highly theoretical assumption put forward as a deduction: a great many other and diverse theories may equally be derived from the meager statement concerning the relation of volcanic eruption and faulting.

Later, he summarizes his views:

"We may conclude, then, that the chief cause of the eruption of magma is the dislocation and fracture of the lithosphere, and that to some extent it may be aided by the slight expansion of magmas upon diminution of pressure, whether they are in the beginning wholly amorphous matter or in part crystals. It is aided when near the surface by expanding gases. Eruption may also result in part from hydrostatic pressure, due to the settling in some instances of overlying rock masses which may rest upon bodies of magma within the lithosphere in a manner to be discussed later on.[7] . . .

"Owing to the approximate equality of mass and pressure between what may be called the wall matter and the penetrating moving magma, fissures filled with magma may exist at any depth. . . .

"The progress of magma upwards depends upon the dislocation of the fractured lithosphere. Molten magma is probably a passive agent at profound depths. It cannot be the potential cause of eruption. Unless there has been a

[6] "The Problem of Volcanism," 1914, p. 165.

[7] *Op. cit.*, p. 174.

profound movement of the lithosphere, it seems to be safe to say that magma will not rise, will not force its way upward.[8] . . .

"The conception of magmatic eruption which has been suggested involves a comparatively rigid upper zone of lithosphere, grading downward into a pseudo-rigid zone having essentially the same chemical composition as the upper one. It also involves the idea of a warping lithosphere adjusting itself to a contracting central mass; the warping producing fractures along which the highly viscous matter moves according to differences of stress, and in the process becomes less viscous as it approaches higher levels, attaining its maximum liquidity where the gaseous constituents have their freest movement, or are concentrated in greatest amount; magma coming to rest in equilibrium with surrounding wall rocks at various depths, and in some cases finding itself in equilibrium with the atmosphere at the surface of the earth.[9] . . .

"These magmas, having nearly the same density as the wall matter, and a hydrostatic pressure corresponding to their depths below the earth's surface, are able to support whatever load is above them, and for these reasons may permit the walls of the fracture to separate vertically or laterally, whenever the stresses acting within them tend to move them apart. . . .

"The lack of homogeneity in the mass of the lithosphere permits the unequal warping or flexure of the parts separated by fracture; that is, beneath as well as above the planes of fracture; so that with the intrusion of dense viscous magma it is possible for the upper and lower walls to separate sufficiently to allow large volumes of magma to insert themselves in some places.[10] . . ."

I quote the above extracts simply as an example of one form of current theory; it is a conception based almost

[8] *Op. cit.*, p. 175.
[9] *Op. cit.*, p. 185.
[10] *Op. cit.*, p. 194.

wholly upon imagination, and is one which my own imagination refuses to follow. The spectacle of the solid rocks at great depths moving wide asunder to permit the inflow of fluid magma to form dikes, or of overlying rocks lifting themselves by their bootstraps, as it were, to make a horizontal fissure into which they courteously permit magma to enter to form an intrusive sheet or sill, does not appeal to my imagination as possible.

Daly, on the other hand, has elaborated a theory of igneous intrusion, especially for great intrusive masses, bosses or stocks of granite, by which they eat their way up toward the surface, by spalling off of blocks from the roof, which are either dissolved and assimilated by the magma, or, if heavy, are sunk to the depths; so that the magma continually rises and broadens. He compares the process in his thought to the mining operation called "overhead stoping," where the miners break ore from the roof of the chamber or stope, and, standing on the broken ore which has fallen, break anew from the roof, and so mount up.

The conception of Daly is one which appeals to the imagination as plausible. To what extent this process is operative, if at all, I have not formed a clear opinion; but at least I have not found in my experience much field evidence to lead me to adopt his explanation. Phenomena of complex intrusion, to be sure, are common on granitic contacts; but this would be the case on any theory; and I see in the intrusive phenomena of great granitic bosses the same problem as in the case of the intrusion of narrow granite dikes, between which bosses and dikes one may find gradations; and I find the same intrusive phenomena and problems in granite, diorite, or peridotite dikes or masses of all sizes. The differently composed magmas and the various forms of intrusion indicate, to my mind, a single general problem and call for a single main explanation.[11]

While in Saskatchewan, in the belt described in Chapter II as characterized by intrusive granitic rocks and mineral

[11] Note at end of Chapter III (p. 184).

veins, I noted some phenomena of intrusion which, it seems to me, have a very plain and important lesson.

A gray granite covers much ground, over the whole belt traversed—several hundred miles from west to east. In the western part of the belt it is massive, but becomes increasingly gneissic toward the east, and is highly gneissic and metamorphosed at Wintering Lake, near the eastern end of my traverse. Another and more siliceous granite, characterized by reddish feldspars, was also noted at intervals along the whole belt, but especially in mass in the eastern part, where the gray granite becomes increasingly gneissic and metamorphosed: on Paint Lake and Wintering Lake I found the red granite intrusive into the gneissic and metamorphosed gray granite. This red granite has no gneissic structure, and occurs in the various forms of granite, pegmatite, and aplite; it has a close connection with both ore deposition (gold, molybdenite, chalcopyrite, pyrrhotite, etc.), and metamorphism (development in the older granite-gneiss of garnet, pyroxene, pyrrhotite, etc.).

Where we find a massive granite like this, intrusive into a granite which has been altered into a gneiss, our usual interpretation is that subsequent to the intrusion of the first granite (it is intrusive into older greenstones of diverse origin) it has been affected by pressure and changed to a gneiss; and at a subsequent time the massive red granite was intruded. I have been accustomed to visualize a dynamic force of great magnitude operating between the periods of intrusion of two granites such as these.

On the shore of a little lake called by the Indians Pokatohogan, about midway in the belt, I had the luck to study some phenomena which I shall not soon forget, for the surprising lesson they taught me as regards intrusion and the development of gneissic structure.

Here the older gray biotite granite is highly gneissic, the lines of gneissic structure being very straight, close, and parallel. It is split and intruded, parallel to the gneissic structure, by dikes of alaskite, belonging to the later red

granite intrusion, and without gneissic structure. These dikes at the point examined are up to 30 feet across, but to the west of here the alaskite was found in immense masses. There are here (at Lake Pokatohogan) smaller pegmatite veindikes belonging to the same red granite series and without gneissic structure, which either lie in and parallel to the alaskite dikes, or have the gray gneiss-granite for walls.

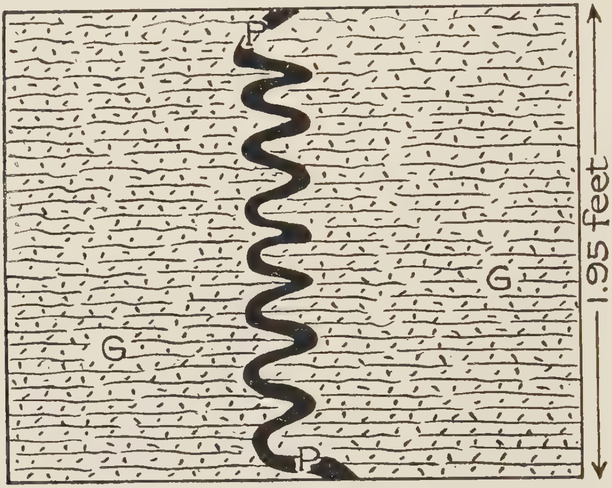

Fig. 34.—Lake Pokatohogan, Manitoba, Canada. Outcrop (horizontal plane) of narrow pegmatite veindike in gnessic granite. Length of exposed portion of veindike has been shortened by compression during rock-flowage, which has resulted in gneissic structure at right angles to strike of veindike. Present length of veindike, 1.95 feet; original length, 3.9 feet. Shows horizontal compression of granite, to form gneiss, of 50 per cent, or two volumes into one, in the direction at right angles to gneissic flow-lines. G, Gneissic granite; P, pegmatite of gneissic granite period.

Latest of all are certain pegmatitic quartz veindikes, representing also the red granite series, which lie in the pegmatite sheets, or occur independently in the gneiss.

Pegmatites and pegmatitic quartz veindikes, as we are now well aware, may characterize the closing stages of any granitic intrusion; and accordingly we find here, in the gray gneissic granite, narrow pegmatite veindikes which are older than the later red granite series of alaskite, pegmatite, and

quartz, and which have been affected, with the gray granite, by the gneissic deformation. And the effect of the gneissic deformation on these narrow veindikes belonging to the gray granite period throws a great light on the nature of this deformation.

Figure 34 shows such a narrow pegmatite stringer, a few inches wide, which runs at right angles to the gneissic structure, and to the later granitic intrusions. The effect of the gneissic deformation was to fold this back on itself like an accordion, regularly, showing a uniform compression at right angles to the gneissic structure. I carefully measured with a string the original length of this little veindike, and the present length; originally, in the space sketched, it was 3.9 feet long; now it is 1.95 feet. The granite (as shown by the crumpled veindike) has been compressed almost exactly 50 per cent by the gneissic deformation, along a horizontal line perpendicular to the vertical gneissic structure. This diminution of original extension in this direction must indicate a loss of volume due to flowage, for certainly the density of the rock is the same now as before the gneissic structure was introduced; the gneissic structure is therefore essentially a flow structure, produced by a crystalline rock flowing slówly under overwhelming pressure.

Whither did the lost volume of granite flow? Was there horizontal elongation of the rock parallel to the gneissic structure, to compensate for the shortening on the horizontal axis perpendicular to it? In this connection note Fig. 35, sketched at the same place (Fig. 36 is a detail of Fig. 35 sketched very carefully). Here we have a crumpled pegmatite ribbon of the older series running diagonally to the subsequently induced gneissic structure; its original length, between the two later pegmatite bands, was 19.6 feet, and it has been shortened by the gneissic flow to 13.5 feet, a shortening of 6.1 feet, a diminution of one-third. The occurrence as sketched shows reduction of length (and consequently of volume of the granite) on the horizontal plane of the exposure, not only perpendicular to the straight

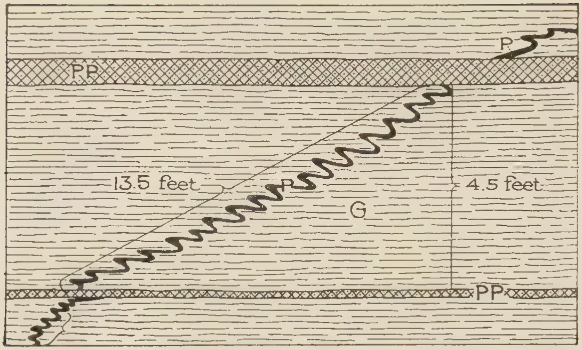

Fig. 35.—Lake Pokatohogan, Manitoba, Canada. Outcrop (horizontal plane) of crumpled narrow pegmatite veindike in gneissic granite. Gneissic granite has been intruded, parallel to gneissic structure, by later unsheared pegmatite veindikes. G, Gneissic granite; P, pegmatite of gneissic granite period; PP, pegmatite of subsequent unsheared granite period. Between the two PP veindikes, the earlier P veindike has been shortened to 13.5 feet from an original length of 19.6 feet, a diminution of one-third. This sketch shows that granite in becoming gneissic has had its volume on a horizontal plane diminished not only at right angles to the gneissic structure but parallel to it; showing flow in vertical direction.

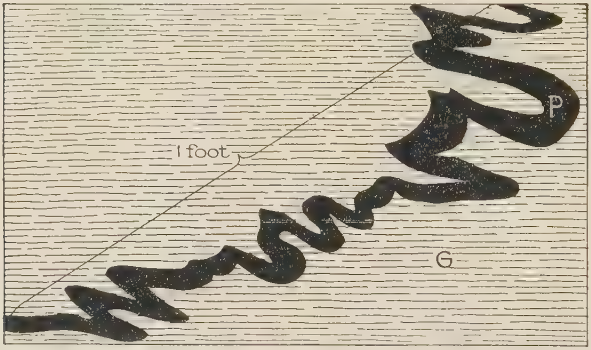

Fig. 36.—Lake Pokatohogan, Manitoba, Canada. Larger-scale sketch of portion of narrow pegmatite veindike shown in Fig. 35. In this section the measured original length of the veindike was three feet, and it has been compressed into a length of one foot, or one-third its original length. This proves that the compression of volume of the gneissic granite by upward flow was not uniform, but varied in different zones. G, Gneissic granite; P, pegmatite veindike of gneissic granite period.

regular lines of gneissic flow, but also parallel to them. In other words, the granite here flowed either in an upward or a downward direction; and we may safely assume that it was upward, since relief of pressure was possible only in this direction. The angle of this contorted pegmatite band, with the schistosity, is about 22°,[12] and, by plotting it out, we find that the band has been shortened in a direction parallel with the gneissic structure from about 18.25 feet to 12.5 feet, and, in a direction perpendicular to it, from 7.2 feet to 4.5 feet, a shortening of about one-third in each direction. In this case, therefore, the direction of gneissic flowage was *vertically up*.

The two cases just cited, however, one showing a compression of 50 per cent and another of 30 per cent perpendicular to the vertical gneissic structure, prove that the amount of flowage differed in different bands or zones, and this is shown by Fig. 36, which shows the shortening of an extension of the same pegmatite band as depicted in Fig. 35, from 3 feet to 1 foot, a shortening of two-thirds instead of one-third. Similarly, two adjacent segments of another crumpled pegmatitic band, perpendicular to the gneissic structure, show original lengths of 12 and 15 inches respectively, shortened respectively in the proportion of 4 into 1 and 5 into 1. The greater flowage along certain bands is well shown in Fig. 37, which shows compression along both horizontal axes, and in Fig. 38, which shows a shortening of nearly 2 into 1 (3 feet into 1.6 feet), mainly localized along a narrow zone. The gneissic lines, however, are universally and strongly developed, and indicate everywhere compression at right angles to the vertical gneissic planes, and frequently compression (and never extension) on a horizontal line parallel to these planes. A rough estimate of the average compression or shortening at right angles to the gneissic planes is 50 per cent, or 2 into 1, with a distinctly lesser shortening along the other horizontal axis.

Along the margins of the larger alaskite dikes the gneissic

[12] The sketch is therefore slightly inaccurate as to angle.

flow structure is very noticeably and strongly intensified, being the maximum noted in the exposures, and occurs in such a way as to indicate that the flowage is connected with and due to the lateral pressure of the dike intrusions.

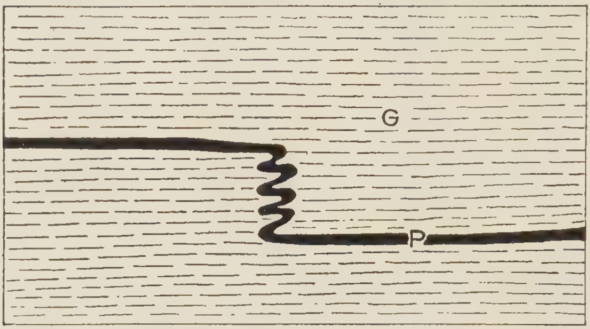

Fig. 37.—Lake Pokatohogan, Manitoba, Canada. Narrow pegmatite veindike (P) in gneissic granite (G). Shows compression of rock both parallel to gneissic structure, and, more powerfully, at right angles to it. Compression parallel to gneissic structure is local.

This striking local relation, together with the general fact that the development of this universal gneissic (flow) struc-

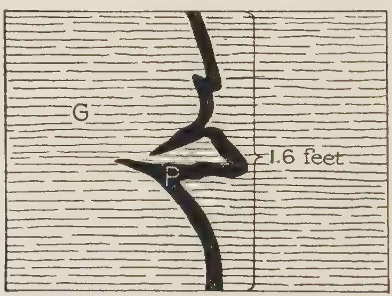

Fig. 38.—Lake Pokatohogan, Manitoba, Canada. Outcrop (horizontal plane) of crumpled narrow pegmatite veindike (P) in gneissic granite (G). Shows compression of granite in line at right angles to gneissic flow, but varying markedly in different gneissic zones. Present length of veindike, 1.6 feet; original length, 3 feet. General compression of two into one, but in the center of the figure, locally, much more than that.

ture in the older gray granite coincides with the appearance of large areas of the intrusive massive alaskite of the later granitic epoch, indicates that the origin of the gneissic

structure was not antecedent to the intrusion, but accompanied it, and was in fact caused by it. The proof given above of the contraction in horizontal section of the volume of the older granite shows that the wide spaces occupied by the later intrusions did not yawn open gently and permit the later granite to come up, a process involving distinct tension (if it were conceivable at all, which it is not), but that the intrusion was marked (or, even on any other theory, preceded) by intense compression.

Roughly, the reduction of the amount of the older granite by gneissic flow, as measured in horizontal section, appealed to me in the field (in default of any systematic mapping) as perhaps about the same as the amount of new intrusive granite introduced; so that the thought came to me that just so much of the older granite had been displaced by flowage as was forced to do so by the advent of the later intrusions (varying from small dikes to large intrusive masses), which thrust themselves from below into this zone, under a pressure greater than the strength of the solid rocks which they invaded.

This process of intrusion and flow was apparently a leisurely one. Some miles east of the occurrences described above, on the east side of Setting Lake, trap dikes cut the granitic gneiss and are themselves locally involved in the shearing, although not to the same extent as the granite. Most of the older contorted pegmatitic veindikelets came in before these trap dikes, but a few of them intersect the dikes, showing that the dikes appeared during the latter part of the earlier pegmatitic intrusion. Veindikelets of the later unsheared pegmatite cut the trap dikes as well as the gneiss and the older pegmatite. Still further east, at Lynx Falls, the rock becomes more and more gneissic, and the trap sheets are locally broken and shredded, as shown in the sketches (Fig. 39). The trap evidently was less plastic and was torn and strung out by the greater flow of the more plastic granite, now transformed into a siliceous gneiss. The lines of gneissic flowage curve around the

broken fragments of trap.[13] Thick sheets of trap, however, have been rendered gneissic, being too thick to allow the pressure to be taken up by the flowage of the older siliceous rock, as in the case of the figures sketched. At Lynx Falls this was observed on a large scale, and the veindikelets of the earlier pegmatite in the trap have become contorted by the flowage. Here the crumpling of veindikelets running perpendicular to the strike of the gneiss is like that at Lake

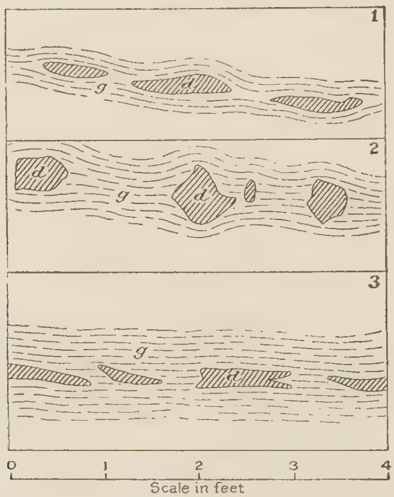

Fig. 39.—Near Lynx Falls, Manitoba, Canada. Trap dikelets *(d)* in granite gneiss *(g)*, shredded by extension of rock parallel to gneissic flow; (1, 2, and 3 show various exposures of these trap dikelets).

Pokatohogan, indicating an average compression of the original trap rock, along this axis, of over 50 per cent; but parallel with the gneiss strike there has been no compression, as at Lake Pokatohogan, but, instead, extension, as shown by the effect on those veindikelets of pegmatite which are parallel to the gneissic structure. These show typically a certain elongation, thinning, and sometimes pulling apart of the veindikelet, indicating an average elongation, along this axis, of the rock, which, however, is

[13] The accompanying sketch, as rendered by the draftsman, is slightly inaccurate in this respect.

relatively slight, and was estimated as averaging 10 to 20 per cent. The elongation parallel to the gneissic structure of the siliceous granitic gneiss west of Lynx Falls (Fig. 39) is greater than that just given for the trap gneiss, and varies in different bands from 10 to 200 per cent or more. Note that if the whole compression on a horizontal plane were taken up by elongation in the same plane, a compression to 50 per cent of the original thickness would be compensated by an elongation of the original length by 100 per cent. Now, in the siliceous gneiss which shows the greater elongation above mentioned (10 to 200 per cent), the compression of original thickness is very great, and from many observed cases was estimated as averaging 4 or 5 into 1. Along this stretch, on Grass River and around Lynx Falls, the compression of the siliceous granitic gneiss is estimated on the average to be three times (or more) that which can be accounted for by longitudinal extension: therefore the main direction of flowage must still have been upward, at an angle of 65° or more from the horizontal.[14]

The area occupied by this gneiss is very large—I do not know how large—and the observed compression enables us to assume very roughly (and simply for the purpose of visualization) that a column of the older gray granite (now granitic gneiss) equal in horizontal area to that of the present gneiss exposure, and equal in height to the original vertical depth of the gneiss, has been propelled toward the surface—slowly, if we can judge from some of the phenomena above mentioned. If my conclusion that the intrusion of the red granite series caused this flowage is correct, then

[14] If the flowage of a gneiss or schist which shows compression on a horizontal section has been upward, as I have deduced, the field check on this conclusion is obvious: veinlets contorted on horizontal section should show no contortion on a vertical section. I have been able to apply this check in the case of the pre-Cambrian gneiss near my home in New Rochelle, N. Y., by observing repeated instances where pegmatite veinlets are much contorted and compressed along both horizontal axes, but in a vertical section are long and parallel.

this intrusion was also an exceedingly slow process, occupying a very considerable period.

What would be the final effect of such a slow regional upward movement? Evidently, since the possibility of actual rock compression is negligible, a movement of this magnitude must affect the surface of the earth, and be expressed by a slow local uplift of the sort we are familiar with from geological evidence in many regions—a swelling up and doming up of the crust, in extent depending upon the dimensions of the intrusion below but affecting a greater horizontal area. In this Saskatchewan area, the granitic and alaskitic dikes are but the outliers of the main large intrusive masses of granite.

We are familiar with the complex of crystalline gneisses and schists and intrusive granites in many areas, representing ancient and once deeply buried rocks; and, as I noted above, our common conception of the relation of a gneiss or schist to an unsheared intrusive granite is that the earlier rock underwent a great dynamic experience before the granite was intruded. In this Saskatchewan area, I have shown how my conceptions for this area became entirely changed by the local records of the rocks, and I became convinced that the gneissic structure was contemporaneous with the intrusion and was caused by it.

The thought comes to my mind as to whether this may not be the case in many another similar area. Take the Archæan of Colorado, for example. In the Georgetown district the situation was thus expressed by Mr. Ball (it was also my own interpretation):

"The older pre-Cambrian rocks in the Georgetown quadrangle, constituting the Idaho Springs formation, are crystallines, presumably of sedimentary origin. This formation, while deeply buried, was subjected to mountain-building forces which folded it in a complex manner and produced in it a regional schistosity. Later, but undoubtedly also in pre-Cambrian time, it was most intensely intruded by a series of holocrystalline igneous rocks. The earlier of these

rocks were considerably affected by the mountain-making forces which produced the regional schistosity in the Idaho Springs formation, while the later are mashed only along lines of intense local movement. From the different degrees of schistosity developed in the different pre-Cambrian rocks, the period between the deposition of the Idaho Springs formation and the intrusion of the latest pre-Cambrian granite must have been of vast length, and during the long period of intrusion, to judge from the granitoid habit of the igneous rocks, the surface as we now see it must have been buried under a great thickness of overlying rocks." [15]

What were these "mountain-building forces" which produced the schistosity? Can they have been the force of the repeated intrusions themselves? Is it not very significant, perhaps, that the development of this schistosity, this flowage and recrystallization, continued as long as the granitic intrusions continued, involving the earlier of these intrusions themselves, but stopped at once and for all time when the slow process of repeated granite intrusion came to an end—for the latest granites are not sheared, nor the long series of later sediments and intrusions in Colorado, lasting through the whole column of historical geology, from the Cambrian to the present day?

By far the most important intrusive rock, in point of area occupied, in the quadrangle, is the quartz monzonite,[16] which was mapped in a single body ten miles square; this constitutes a portion of a batholith which extends far beyond the eastern boundary of the quadrangle. Ball observes, "The concentric strike of the schistosity of the older rocks around the batholith shows that the igneous mass made room for itself by thrusting aside these older rocks." A study of the geological map, on which the lines of schistosity, as well as the area of the granite, are indicated, shows the general parallelism of the schistosity of

[15] *Professional Paper* 63, U. S. Geol. Surv., p. 37.

[16] *Op. cit.*, p. 51.

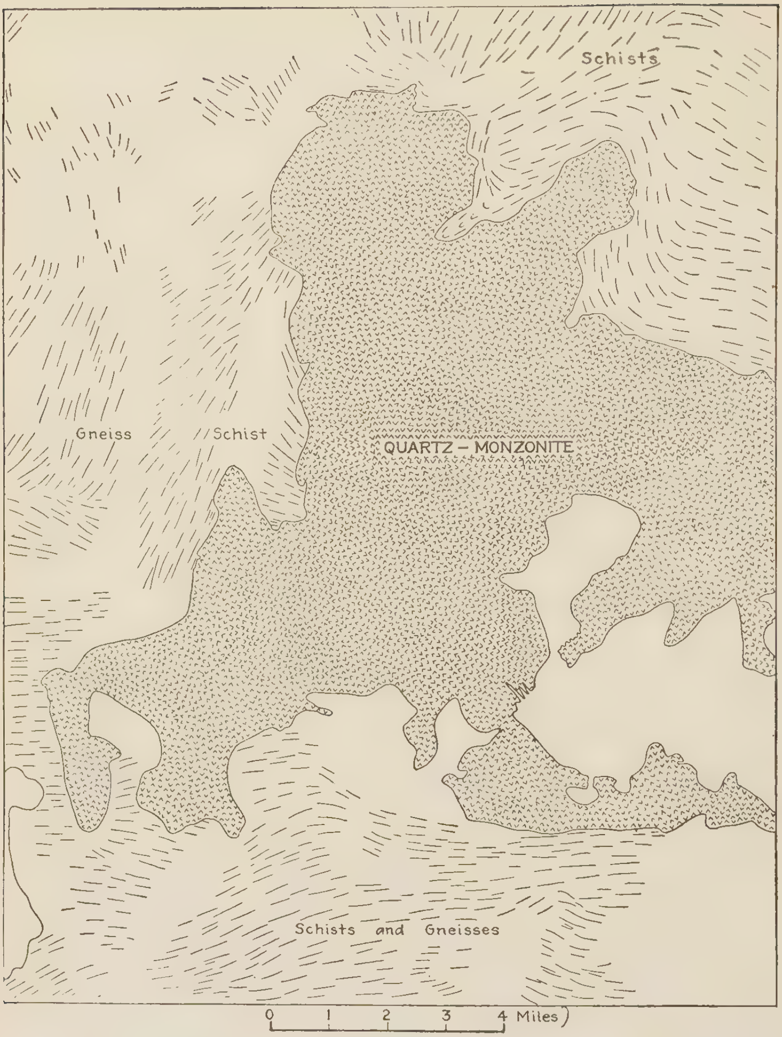

FIG. 40.—Georgetown quadrangle, Colorado. Showing general relation of strike of schistosity and gneissic structure, in intruded schistose and gneissic rocks, to outlines of monzonite intrusion (pre-Cambrian): indicating that the schistosity was induced by the intrusion. Adapted from map by Sydney H. Ball (Spurr, Garrey and Ball: Professional Paper 63, U. S. Geol. Surv.). Blank areas are chiefly unsheared pre-Cambrian intrusives, later than quartz monzonite but inferior in bulk. All the various rocks older than the quartz monzonite are sheared or gneissic.

the invaded rocks to the form of the intrusive granitic (quartz-monzonite) mass (Fig. 40).

Imagine now the adjustments of the older rocks necessitated by being pressed back by ten square miles and more of intrusive magma. The room into which the invader slowly wedges itself cannot be made by compression of the rocks thrust back on themselves; it must, certainly at the great depths at which these events take place, be made by flow—a portion of the invaded rocks flows up past the zone of intrusion, and the intrusion and the adjustment by flowage goes on synchronously; and the planes of flowage must be what we call the planes of schistosity. That it was probably the advent of the monzonite mass which induced the schistosity is shown, on the published geological map, in the southern part of the quadrangle, where the schistosity planes which sweep around parallel to the monzonite contact pass from the older Idaho Springs formation into and through later masses of granite (but earlier than the monzonite) without change, indicating a single main period of development of schistosity, contemporary with and controlled by the main igneous intrusion.

It is to be noted that this conception of slow upward forcing itself of the intrusive magma, with concomitant slow up-flowage of the intruded rock to make room, necessitates the corollary that the flowage continues during the intrusion far up beyond the actual position of the magma at any given period; so that, when the mass finally comes to rest as a batholith or stock, the rock far around, and especially far above, will be gneissic or schistose, even if without intrusive bodies, or showing only relatively small dikes from the great central mass.

That the deformation of the gneiss and schist of the Georgetown quadrangle was indeed accomplished in part at least by flow, is shown by the elongation of pebbles in an ancient conglomerate of the Idaho Springs formation observed near Silver Plume. This conglomerate is now altered into a gneiss, and these pebbles are the only plain

evidences of the originally sedimentary character of the rock.[17] In some streaks these pebbles have practically escaped deformation, and can be easily detached from the matrix, now metamorphosed into a granitic gneiss. Originally they must have consisted of impure quartzite. In many—in fact in most—occurrences these pebbles have been elongated by stretching, so that they become long, flat, and thin, and in the extreme recognizable stages are represented only by siliceous streaks, which would no longer

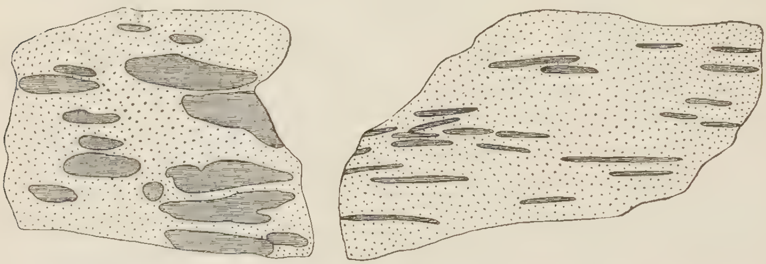

Fig. 41.—Flowage of gneiss-schist near granite intrusion at Georgetown, Colorado, shown by varying elongation of pebbles in probable original pre-Cambrian conglomerate. Traced from photographs (see Spurr, Garrey and Ball: Professional Paper 63, U. S. Geol. Surv.; Plates VII and VIII) and reduced.

be noteworthy or suggestive were it not for the observed transition (Fig. 41). Such elongated pebbles are in places contorted with the inclosing matrix.

Therefore my general interpretation of intrusion is that the intrusive fluid is under pressure strong enough to thrust back, even though slowly, miles of solid rock, from the flanks of a batholithic granitic intrusion, and to lift the rock cover vertically above and force it as a mass upward; and that the same power resides in the magma which forms a dike 10 or 50 feet wide.[18] This I think is evident. As to

[17] *Professional Paper* 63, U. S. Geol. Surv., p. 177, Plates VII and VIII.

[18] In central Missouri, on the border of Camden and Laclede counties, is an intrusive neck of pegmatite (quartz and feldspar) and pegmatitic quartz ("sometimes masses of quartz are found with no admixture of feldspar") which has cut into normally horizontal and undisturbed Lower

what this pressure results from: either it is a transmitted pressure, as has been imagined by many, due to the squeezing of the same body of magma elsewhere between rigid rocks, in consequence of movements in the crust; or it is an inherent pressure and expansive force, which must be due to a compressed state of the magma in the depths whence it arises. The first possibility has been rather vaguely and inexactly called "hydrostatic"; but I am inclined to the second. The portions of the magma which would have the most expansive power if compressed would be the volatile or gaseous elements. We are familiar in a way with the expansive force of shut-in gas. If the gases in these rising magmas are in a compact condition, the expansive force might be very great. In any case this enormous power is evident; and since it must be derived from deep-seated sources, I will call it for convenience telluric or

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Silurian limestone. The actual exposure of pegmatite *does not exceed a few square yards*, and had it not been that the locality was prospected for lead, its presence might never have been detected. The above information and quotation are from Winslow, "Lead and Zinc Deposits of Missouri," Vol. VII, Missouri Geological Survey, p. 432.

An extraordinary interest attaches itself to this pegmatitic neck, not only from the standpoint of ore genesis, but especially from that of the study of the process of intrusion, and the origin of folding and faulting. Immediately around this tiny pegmatite outcrop, the limestones are violently disturbed, assuming dips varying up to vertical, and with varying strikes. This disturbance *extends laterally more than a thousand feet* (see map, Winslow, *Op. cit.*, p. 433), and southwesterly a *zone of highly disturbed strata may be traced two miles!* Well may Winslow say that the intrusion "has pushed its way up through the rocks"! The long southwesterly extension of the disturbance seems to me plainly a betrayal of its subterranean course, like the long surface mound of earth that the mole makes in his burrowing; and indicates a course for the pegmatite not vertically up, but more horizontal, inclined upward to the northeast. Consider, once again, the enormous manifestation of force of this pegmatitic neck, so insignificant in surface cross-section. True, it may be larger in depth; but conceive of the inherent dynamic pressure it exerted, boring its way upward. It parted and shoved back the rocks in its way, with resistless pressure. This pressure, then, inheres in a pegmatite magma as well as in an ordinary granite or diorite magma; indeed, since portions of this outcrop are of pure quartz, this occurrence illustrates my conclusion that quartz magmas have the same intrusive potency.

bathogenic pressure—belonging to the earth or born in the depths.[19]

According to the above, a large or batholithic intrusive body of igneous rock, slowly rising by intrusion in and from the depths, would cause a corresponding uplift of the crust at the surface, both directly above, by direct lift, and on its flanks, by the upflow of displaced rock; so that the form of the dome-like uplift would correspond to that of the intrusion, but the dimensions would be larger and less

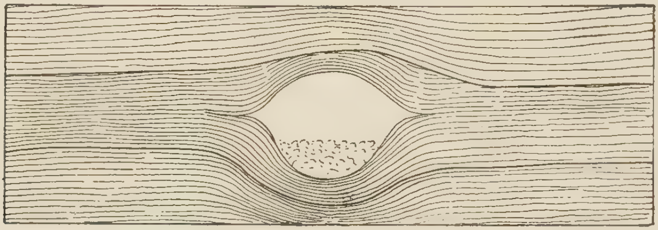


FIG. 42.—Cavities in oil shale in Colorado, produced by the expansion of gases. The power of gaseous tension to thrust aside rocks against an immense overlying load is here illustrated. After C. C. Starr: "Eng. & Min. Jour.-Press," Vol. 133, p. 877.

clearly defined. The lateral flow would diminish gradually as the distance from the intrusion increases, thus insuring a gentle shading off of the whole rock uplift.

[19] Figure 42 shows, according to Charles C. Starr (*Engineering and Mining Journal-Press,* Vol. 113, No. 20, p. 877), a characteristic type of open cavity in certain oil-shale strata in Colorado. Mr. Starr writes that these holes range in size "from an inch or two to six or more feet in diameter. These holes are roughly spherical, but slightly flattened in the direction of the bedding planes; and are partly filled with limonite, gypsum, calcite, and a fine mud or dust, sometimes in the form of crusts or sponges, and sometimes loose. Not infrequently they contain a small amount of solid hydrocarbon, similar to gilsonite, in pieces up to two or three inches in diameter. . . . In the rich shales the strata are somewhat warped in the immediate vicinity of the cavities as though by pressure. Evidence indicates that these cavities were formed by the collection and expansion of gases from organic matter in the stratum after it was buried to a considerable depth, but before it had entirely consolidated."

This is an interesting example of the power of gaseous tension to thrust up and aside great weights of rock; and the manner of intrusion of gilsonite dikes is more easily understood from this phenomenon.

Since the height of the crustal uplift would nearly correspond, as I mentioned earlier, to the height of the intrusion, and since we know that the ascent of such intrusions is to be measured by the thousands of feet, in some cases perhaps many thousands of feet, the uplift at the surface would have the corresponding titanic dimensions. Let us note again that the mechanics of the batholithic intrusions and the upward flow of the rocks on their flanks call for a gradually distributed uplift or doming of the crust, instead of the uplifting of great fault blocks. But if the intrusion be relatively steep and narrow, creating relatively little rock flowage on its flanks and having its main effects of mechanical displacement confined to the forcible uplifting of the rock cover immediately above, then the block of crust above may perhaps break away from the surrounding rocks, and be lifted up as a fault block, or as many small fault blocks.

Just such gradual and distributed uplifts of the crust, of all dimensions, as are postulated above as the result of batholithic intrusions, are familiar to all geologists; and it seems to me an unavoidable conclusion that some of them at least must have had the origin which I have assigned. And as many of these uplifts have been very gradual, climbing up with infinite persistence and slow movements through periods of years so long that we cannot form a mental picture of them in terms of our own experience or of the whole of human history, I am strongly inclined to the belief that we have in this an additional evidence, and, indeed, the clearest evidence, of the immense slowness of some of the bathogenic intrusions.

In studying geology, in the field or in the library, an igneous intrusion, the injection of a dike, narrow or wide, or of a stock or batholith, seems to us a clean-cut event, a point in geologic time, a welcome milestone to mark a definite advance or stage in the evidently immense stretches of geologic duration; and if, as I believe may be true, the average deep-seated batholithic intrusion proceeds at a rate comparable to that of the average local crustal uplift, the

thought refuses to follow or fathom the time significance of the vast stretches of geologic history of which these intrusions seem hardly more than the punctuation marks. And the conception is one which must be extended also, with appropriate modifications, to the narrower dikes of granite and other derived rocks attendant upon the batholiths, and which are contemporaneous, in part at least, with the main masses.

Our usual conceptions of the time occupied for igneous intrusion are doubtless based on the only events of this kind with which we have a personal acquaintance—with volcanic eruptions, which are truly sudden and catastrophic, and involve the sudden flow of large quantities of lava, and probably the filling of fissures by lava, to form what we may term catastrophic dikes. But I think we cannot argue from these phenomena back to the intrusive and other igneous processes in zones far beneath the surface. The relief of pressure, the sudden expansion, amounting even to explosion, which magmas experience when coming so close to the crust that the thin film of rock above must break and be entirely demolished and destroyed, is without parallel or close analogy in depth.

As to the extent of intrusion or surgence [20] of magma in depth, it may be noted that batholiths [21] are characteristic of the oldest rocks, which have been most deeply eroded, and therefore represent the greatest depths which are laid open to our eye. These great stocks, bosses, or batholiths are largely dome shaped, with evidence of (originally) a gently sloping cover, since they have a flat outward dip on several if not on all sides. The inference is that at greater

[20] I have taken the liberty of coining this word. I shall use it frequently. Its meaning is evident. It is from the Latin *surgere,* to rise. It signifies, then, literally, *rising.*

[21] As their name indicates—literally "a deep rock." I dislike to use too freely these Greek terms, which are to many unintelligible, and which are stones apt to be mistaken for bread by those hungry for knowledge; at times, however, they offer a pithiness of expression which would not be obtained by the corresponding English circumlocution.

depth they cover a larger horizontal area, and that many of them may unite to form increasingly larger and larger masses, of which the bosses which we can see are only the protuberances or humps; there is no evidence, and indeed no theoretical probability, of these bodies being cistern-like or reservoir-like in form, like the laccoliths described by Gilbert and Cross in the stratified rocks which lie above the complex crystalline foundation of the crust. These laccoliths are inflated sills, and, like sills, are dependent on and determined by the bedded form of the rocks: sills are injected along the planes of weakness formed by the stratification, and when the telluric pressure of the injected magma is greater than the rock pressure, the magma forces back the rocks in the only direction in which relief is possible—toward the surface, bodily lifting the crust. Hence the rounded upper side, with its bent and pushed-up strata, and the undisturbed condition of its lower side.

By the same token that the thin intercalated flat sills are not characteristic of the crystalline complex, we must dismiss the idea as improbable that the bosses or bysmaliths (plugs) are cistern-like or laccolithic in shape. If it were so, again, we probably should have found the lower contact of some of them—of the high-lying ones, or where erosion has been deepest; but we have not. Our every evidence is that in increasing depth the bosses occupy broader and broader areas.

Now, even the deepest erosion has revealed only a certain depth below the surface; below this, erosion has never gone and never will go, and we are reduced to other and very vague and unsatisfactory methods of obtaining evidence; but it can readily be seen, as a possibility indicated by the facts, that in those deeply eroded regions which show many large bosses of intrusive granite rocks (many of the individual bosses being each many square miles in area, and with flat-dipping contacts away from the igneous domes), the domes may unite at greater depth to form what is or was at the time of intrusion a great underlying magma sea

to whose extent we can set no definite limits, but which may cover or have covered many tens or hundreds of thousands of square miles, at a depth below the surface which, though apparently relatively moderate, is below the zone of possible exposure by erosion.

If the telluric pressure of liquid magmas were mainly a transmitted dynamic exogenic[22] pressure, then it would operate equally for all magmas; if it is endogenic,[23] then it would perhaps be most powerful in the more siliceous rocks, which we have ample grounds for believing have a larger proportion of these gaseous constituents, and would be most potent in pegmatites and allied veindikes. Lavas of all compositions reach the surface in abundance; on the other hand, the great originally deeply buried laccoliths and stocks and batholiths which erosion has uncovered are mainly of the more siliceous magmas—granites, and monzonites, and the corresponding porphyritic rocks.

The basic or less siliceous lavas, it is known, remain very fluid and flow freely at temperatures where the siliceous lavas solidify, the melting point of rhyolite being probably 50 per cent higher than that of basalt[24]; moreover, basaltic lavas are liquid up to near their freezing point, while rhyolitic lavas become very stiff and viscous near their freezing points. That these surface conditions are not necessarily true in the depths is indicated by Fig. 39, above, and the accompanying explanation: here, under the same temperature and pressure, the granite has certainly become more plastic and flowed much more freely than the trap. The explanation may be the same as that which accounts for the fluidity of granite magma at the comparatively low

[22] *I. e.*, born from outside the magma—the result of stresses transmitted from other and rigid rocks. Of "hydrostatic" pressure, as I understand it—that is, pressure due to a higher connecting column of the same magma elsewhere—there can, in my opinion, be no possibility, taking the problem by and large.

[23] Born within the magma, from the expansive stress of its component volatile elements.

[24] Iddings, "Problem of Volcanism," 1914; p. 17.

temperature at which it is believed to exist, as shown by the properties of its constituent minerals—roughly half that of the melting point of the same rock under surface conditions: the gneiss must have flowed by virtue of the presence of volatile elements under pressure, which mixed with the more solid rock constituents in such a way as to render the whole plastic; and it may be that pressure is a greater factor in the keeping plastic and liquid of a siliceous magma than of a basic magma. The main function of pressure in its control over the fluidity and final solidification of a granitic magma would accordingly perhaps be in keeping the volatile elements which liquefy the siliceous magma from escaping.

That the telluric pressure of pegmatites and quartz magmas is tremendous is shown, in my opinion, by various field evidence earlier described; and this inclines me again to the belief that the telluric pressure is inherent rather than transmitted, for the connections of some of these pegmatite and quartz magmas, which form veindikes, must in some cases be quite limited, and it is very doubtful whether they are continuous for great distances to some far-away point where pressure is being exerted. They appear to be rather indigenous—locally born from the parent granitic magma reservoir; the pegmatite exists in a fluid state after the parent granite has solidified, and the quartz magma after the pegmatite has solidified (although all are parts of a continuous process and sequence), and yet each of these retains its property of adequate telluric pressure, and is capable of intrusion almost as freely, apparently, as the parent granitic magma; and since these more persistently liquid segregated or expelled or differentiated magmas are enabled to maintain their combination of volatile elements and dissolved earthy and metallic elements at a lower temperature than the granitic magma, and so keep from freezing, solidification, or precipitation, they may ascend further up, leaving the parent magma behind.

[11] See page 162 for the context. I am not unmindful of the evidence and arguments that have been set forth by Daly ("Igneous Rocks and Their Origin," 1914) and Barrell (*Professional Paper* 57, U. S. Geol. Surv.) for the upward intrusion of batholiths by "stoping," a theory which was, I believe, primarily suggested by the fact that the surface exposures of these batholiths are "cross-cutting"—that is, intruded strata run squarely into them instead of curving around them, whence Daly argues an origin by replacement, instead of by that displacement which characterizes a laccolith or dike. (Daly, *Op. cit.*, Fig. 64.) But volcanic necks have often this same characteristic (Daly, *Op. cit.*, Fig. 145), so that this characteristic alone does not prove replacement. Moreover, this characteristic is not confined to granite batholiths, but is found in very basic domical intrusions, as shown in Fig. 93, which shows some pressure phenomena (adjustment of schistose structure to the outline of the intrusive norite contact), but more marked cross-cutting characteristics. In this case it is very doubtful whether schist blocks could have sunk in the heavy norite magma, although I have no figures at hand bearing on the question. Such phenomena, I grant, either mean "replacement" (which Daly and others believe has been secured by "stoping"), or it indicates vertical displacement of the cover with or without vertical flowage of the walls. In the case of a volcanic plug, or even of a plutonic plug, the cover has often thus been lifted without much noticeable disturbance of the walls. Some of Daly's sections of batholiths seem to be more in the nature of plugs (his Fig. 46). Barrell's sections of the Marysville batholith show considerable uplifting of the cover by faulting, and he records that this is part of a greater batholith which has domed up the sedimentaries above. probably nearly 3,000 feet, and observes (*Op. cit.*, p. 88), "the intrusion of the batholith itself was the cause of the domed structure." Active intrusive potency, therefore, did inhere in this batholith. As to the process of magmatic stoping, I am ready to believe that it may sometimes take place, although personally I have never seen evidence of it; and the evidence stated by its supporters is chiefly theoretical. In any event, I am inclined to assign to it a minor rôle: and I believe it a mistake to assign intrusive or surgent potency to laccoliths, dikes, and plugs, and not to other shapes of igneous rocks, such as batholiths; in which I take the view of Brögger.

This phenomenon of intrusions cross-cutting strata or gneissic structure with little or no disturbance, which phenomenon is the basis for the "stoping" hypothesis of intrusion, demands further study. If we abandon the "stoping" hypothesis—and I fear we must, as a general explanation, since it apparently does not satisfy all of the exhibited conditions—we still have a most perplexing problem. Not only may plutonic intrusions of very heavy magmas (Fig. 93), in which inclosed blocks of wall rock would hardly sink, have the same cross-cutting feature; but volcanic necks of solid lava may cut through horizontal strata with practically no disturbance of the beds, such as the basalt neck figured by Archibald Geikie (A. Geikie: "Ancient Volcanoes of Great Britain," 1897, Vol. II, Fig. 297; also Fig. 238). In the same volume (Fig. 322) a dolerite (basalt) sill is shown cutting diagonally across beds of sandstone and limestone, without

disturbing them. Here (on account of the relative specific gravities) there can be no question of stoping, any more than of assimilation. James Geikie ("Structural and Field Geology," 1920, p. 201) describes a case where thick but discontinuous sheets of basalt have been intruded along sandstone and shale beds: he says: "In short, the distance between two given horizons is neither increased nor diminished by the presence or absence of the intruded sheets"!

Both James Geikie and Archibald Geikie incline, though not very strongly, toward the view that the intruded rock which has apparently disappeared has been dissolved and assimilated by the magma. They do not consider seriously the "stoping" hypothesis. With Daly (essentially), I reject the solution and assimilation theory as a competent explanation

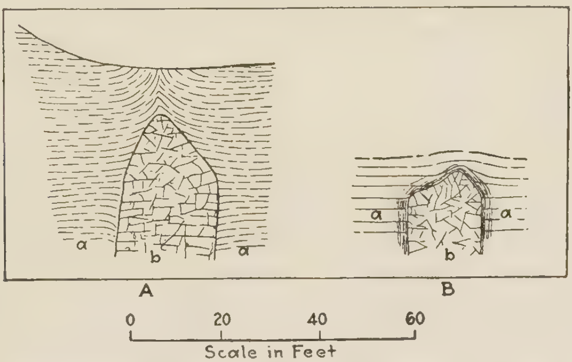


FIG. 43.—Vertical sections across the extreme upper limit of the Cleveland dike, in England. This dike is 190 miles in length. This shows, to my mind, the intrusion upward of a dike "as a knife cuts through cheese."

A, Dike intrusive into Jurassic shales; a, shales; b, dike.

B, Dike intrusive into Carboniferous shales; a, shales; b, dike.

First section after Barrow. Second after Teall. Both from A. Geikie, "Ancient Volcanoes of Great Britain," 1897, Figs. 243 and 244, p. 149.

of intrusion; and if the "stoping" hypothesis is likewise discarded as a competent explanation (and I feel that it is necessary to do this), then we are by the process of elimination thrown back on the theory of forcible intrusion; and must face these apparent anomalies from this theorem. I will leave the reader—and myself—with a certain problem to study: that raised up by the upward terminations of the Cleveland (basic) dike in England. Fig. 43 is a copy of Figs. 243 and 244, by A. Geikie, in the volume above referred to; they are vertical cross-sections of the *top* of an extraordinarily strong and persistent dike, intrusive into shales. Fig. 43-A shows the upper point of the dike as a basaltic wedge being driven upward; the strata next the point of the wedge are bent up: but against the vertical sides of the dike which has followed the wedge-point the shales are horizontal and practically undisturbed! And with the blunter

top shown in Fig. 43-B, even the strata above are only very slightly bent up! In this case, for our theory of intrusion we must eliminate not only assimilation and "stoping," but the theory of the mechanism of the "punch" in so far as this last theory involves the carrying upward, along with the magma "punch," the uplifted and displaced cover. To use a homely simile, but an enlightening one, the Cleveland dike has evidently cut upward through the strata *as a knife cuts through cheese.*

In the case of volcanic plugs the intruded horizontal strata are even very apt to dip down against the plug, evidently the result of sagging of the plug after consolidation. Apparently, friction of the dike against the walls developed only after consolidation, and did not exist in the fluid magma; hence the frequent lack of dragging up of walls by magma which certainly moved up, past the walls. Thus, in Fig. 43-A, the lower part of the figure actually shows a slight *downward* drag of the shale by the dike walls! The greased knife slipped through the cheese without friction, the only disturbance being the pressure at the point of the knife. Therefore, our first dynamic problem will be as to the distribution of displacement (not replacement) which happens when a knife is slowly forced through a cheese, or a nail driven through wood.

These and other shapes of intruded objects will find their analogy in known injected igneous masses. The displacement will probably be found to be massive where that is the method of least resistance, and distributed by widespread flow where the resistance to massive displacement is too great. In the case of a laccolith the displacement is upward, and the comparatively slight resistance of the weight of the block between the intrusion and the surface is overcome by the telluric pressure of the magma. But in the case of the horizontal pressure on the walls of a vertical dike in depth, the resistance to massive displacement horizontally is infinite, and the displacement must be taken up by far-distributed flow. A dome—like the uppermost protrusion of a batholith, whose intrusive contacts vary from horizontal to vertical—will partake of the characteristic of both sill (laccolith) and dike, and the displacement will be partly by vertical uplift—massive displacement—and partly by far and equally distributed rock-flowage. And in the described phenomena of batholith contacts we find many examples of all of these types of intrusion, varying between the laccolith type and the dike type. The slower the movement of the intrusion, the more perfect the flow; the more rapid, the greater likelihood of violent rupture or massive displacement. But the flow will ordinarily and mainly be ultimately translated into distributed surface uplift.

CHAPTER IV

Igneous Surgence on Local, Regional, or Continental Scale

This chapter treats of domical uplifts, on a local or regional scale, in the United States and Mexico. Not only doming, but folding and faulting—even overthrown folds and overthrust faults—may be due to magma migration. On a large scale, the Mexican Plateau, and indeed the whole Cordilleran plateau, may be due to magma surgency or buoyancy. The Sierra Nevada is a fault block of continental-unit dimensions, repeatedly uplifted, probably by underlying magma surgency. Probably a magma basin underlay the whole western part of North America at the close of the Cretaceous and still so underlies. Recurrent upsurgings of this magma bring it into the zone of differentiation, and each upsurging begins a new differentiation cycle. The magma supplies must ultimately be drawn from under the Pacific Ocean basin. Thus the transfer of material from the ocean to the land by erosion is eventually compensated by subcrustal flow from beneath the ocean to beneath the land crust. Exact balance, or isostasy, rarely exists: the subcrustal tides have a momentum which overweights the continents; and there follows from the overweight a sagging, local and continental, which results in rim depressions adjacent to heavy land masses—such depressions as the "foredeeps" of the Pacific.

IN THE PREVIOUS CHAPTER, I mentioned Gilbert's discovery of the laccolithic form of an intrusion, involving an updoming of the intruded strata on the upper side of the laccolith, and to Cross' subsequent investigations and ratification.

Later on, Russell[1] called attention to the fact that throughout the whole of this western Cordilleran region of the United States, intrusive igneous rocks were common not only in the form of intrusive sheets and laccoliths, but also as pipes, which never reached the surface, but worked their way upward as a columnlike development. These were aptly called "plutonic plugs" by Russell, and later by

[1] *Jour. Geol.,* Vol. IV, pp. 25, 189.

the "professionals" called bysmaliths, a rather poor substitution.

In 1898, I published a study of the geology and ore deposition at Aspen, Colorado.[2] This district lies at the western foot of the Sawatch range, which forms the continental divide of the Rocky Mountains of Colorado, and just east of the lesser mass of the Elk Mountains. The rock formations of the district comprise pre-Cambrian granite, and a succession of strata representing the Cambrian, Silurian, Devonian, Carboniferous, Triassic, Jurassic, and Cretaceous periods. From the beginning of the Cambrian up to the close of the Cretaceous, the sedimentary rocks show very slight unconformities or other evidence of disturbance. There is evidence, throughout this vast period of time, of immense periodic elevations and subsidences, producing erosion intervals and other phenomena. Thus there was a subsidence of the pre-Cambrian island[3] in the Middle Cambrian, which subsidence continued into the Silurian; and there was a general elevation at the end of the Silurian.

Omitting relatively minor oscillations, of which there is evidence, there took place during the Lower Carboniferous, a subsidence, and at the close of the Lower Carboniferous a great upheaval again, and this was followed by a profound, gradual, and long-continued subsidence which extended through the latter part of the Carboniferous and the Triassic. At the close of the Triassic there was a considerable uplift, followed by a depression in the late Jurassic-early Cretaceous period; and in turn this was succeeded by an elevation in the latter part of the Cretaceous. This last elevation, at first gradual, became more active, and culminated in the violent uplift toward the close of the Cretaceous and the beginning of the Tertiary. This last upheaval lifted above the sea the whole mass of the Rocky Mountains in Colorado.

The great successive upheavals and subsidences from

[2] *Monograph* XXXI, U. S. Geol. Surv.
[3] C. D. Walcott: Bulletin 81, U. S. Geol. Surv., 1891, p. 368.

the pre-Cambrian to the close of the Cretaceous were not accompanied, in the Aspen district (and for that matter in the rest of Colorado), by igneous activity, at least in that superficial portion of the crust to which we have access; but the final great uplift, at the end of the Cretaceous, was accompanied by the intrusion, as sheets, dikes, and laccoliths, of great masses of magma, as if the uplifting were accompanied by the accumulation of molten rock beneath the crust.[4]

If then the final great uplift was accompanied by accumulation of magma and migrations of magma into the superficial portion of the crust, is it not a fair assumption or working hypothesis that the earlier recurrent mighty elevations were also connected with magma accumulation and migration, albeit none of the magma reached the superficial portion of the crust?

At Aspen the intruded rocks are quartz porphyry and diorite porphyry, in a general way nearly contemporaneous. While the district was subjected to intense folding and faulting, these phenomena followed upon the intrusions instead of accompanying them; the igneous sheets have participated in all that the region has undergone in the way of folding and faulting.[5] The frequent evidence at various places of profound faulting, beginning subsequent to the intrusion of igneous masses, has been touched on by myself in a separate paper.[6]

The profound folding and faulting of the Aspen district, though it followed the advent of the exposed intrusions, appears to have followed *directly* upon these intrusions, and therefore probably has a genetic connection with them. At any rate, the coincidence is significant, that the first great epoch of superficial magma migration in the district since pre-Cambrian time was also accompanied by the first

[4] *Monograph* XXXI, U. S. Geol. Surv., p. 44.

[5] *Op. cit.*, p. 53.

[6] "The Relation of Ore Deposition to Faulting." *Econ. Geol.*, Vol. XI, p. 601.

great epoch of profound folding and faulting (in the same portion of the superficial crust—the only portion with which we have a personal acquaintance), so that the genetic relationship can hardly be doubted; and where, as in the Aspen case, the folding and faulting *follow* the recognized intrusions, it is a fair and, indeed, it seems to me, unavoidable conclusion, that the dynamic disturbance is a *consequence* of the magma migration. This is contrary to the customary assumption of the relation of dynamic disturbances to igneous intrusion—namely, that the intrusion was a consequence of the folding and faulting, although I am not aware that this assumption has been founded on actual evidence.

Two questions now arise: Since the observed intrusive sheets and dikes at Aspen are antecedent to the folding and faulting, and yet a genetic relation between intrusion and dynamic disturbance is indicated, to what act or function of magma migration may the dynamic disturbance be ascribed? Second, what is the cause of magma migration or intrusion into the superficial region? In this connection let us note briefly the stages of deformation in the Aspen district.

The first important movement was an uplift along the granitic axis of the present Sawatch range, so that the sedimentary beds were uptilted and dragged up on the flanks of the granite, with the development of "bedding faults" by the slipping of one upturned stratum upon another, with the weakest beds as gliding planes. This uplift of the Sawatch range was gradual and powerful, as revealed by the study of these faults. There was also apparently a lateral thrust, producing a local narrow zone of close folding, terminating in a very heavy fault—the Castle Creek fault.

Just east of the Castle Creek fault there began, probably about the same time as the other disturbances, but continuing long afterward as an entirely independent disturbance, a very local doming up, which is one of the most interesting

structural features of the district. The summit of the dome is traversed by an intricate system of faults, which have

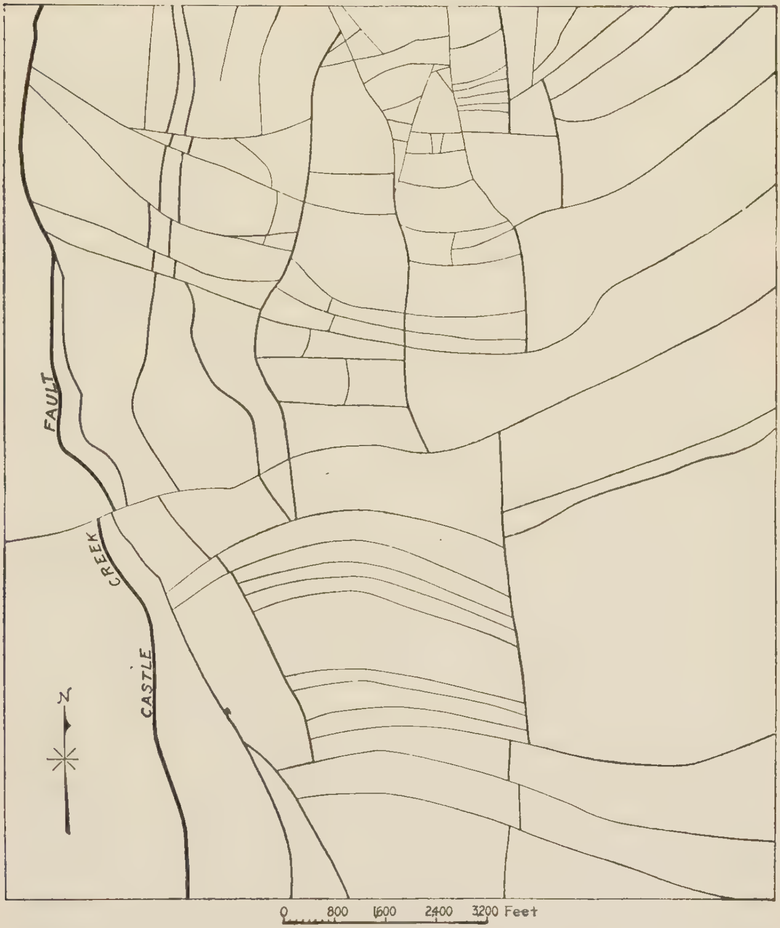


FIG. 44.—Faulting in Tourtelotte Park section, Aspen, Colorado. Heavy lines indicate heavier faults; light lines, relatively lighter faults. From J. E. Spurr: Monograph XXXI, U. S. Geol. Surv., Atlas, Geology Sheet XII.

their greatest development at the point of greatest uplift, and the study of these faults shows their gradual growth and the consequent gradual growth of the domal uplift

(Fig. 44). Ore deposition followed the fracturing and faulting at the beginning of the uplift, and the area of main ore deposition coincides in general with the main area of domal uplift.[7]

This local uplift (affecting mainly the section now called Tourtelotte Park) has apparently no relation to the structure of the surrounding rocks. It does not seem probable, therefore, that it has been formed by any regional stress or lateral thrust, but is such as might be formed by a vertical push from below by some localized force. The period at which its formation began followed intense eruptive activity; the intruded igneous sheets connect with dikes passing down through the pre-Cambrian granite, indicating that these sheets were derived from some deep reservoir. A possible explanation of the domal uplift, therefore, is that magma, probably derived from the same reservoir as the previously intruded porphyry, accumulated in a restricted area just beneath the superficial crust; that upward propulsion of this rock elevated the overlying rigid formations, producing flexing, fracturing, and faulting. We may conceive that if this upward tendency of the magma had been actively continued, the rock would have forced its way to the surface, and what is now the limited, faulted, uplifted dome would have become the neck of a volcano.[8]

The faulting which marks the crest and flanks of the dome at Aspen has continued to the present day, as shown not only by post-glacial growth of the faults, but also by movements along them since the opening up of mines. The maximum vertical movement caused by this doming is estimated at about 5,000 feet, while the diameter of the area affected is not much greater.

If the above hypothesis is a true one, it is to be remarked that we have in the hypothetical slowly lifting "plutonic plug" at Aspen a magma body essentially different from the intrusive sheets and laccoliths which are common in the

[7] *Econ. Geol.*, 1909, Vol. IV, p. 302.
[8] *Monograph* XXXI, U. S. Geol. Surv., p. 148.

more superficial portions of the crust now exposed, and whose form is determined by stratified rocks. This plug lies in the pre-Cambrian granite and has been uplifting slowly ever since the epoch of igneous intrusions at the close of the Cretaceous; has, in fact, slowly lifted its powerful head during the whole of the Tertiary period, keeping pace with a considerable degree of fidelity to the stripping of the cover of the dome by erosion.[9] The load when the domal growth began was at least 15,000 vertical feet more than at present.

If the Aspen dome has the origin above suggested, it may be further assumed that the uplift of the Sawatch range which occurred near the beginning of the doming, and may have grown along with it, was due to a similar process. As above stated, the Aspen dome lies on the flanks of the Sawatch uplift and may be a local manifestation of the same force. As in the case of the Aspen dome, the greater Sawatch uplift has its roots deep in the pre-Cambrian granite which now forms the mass of the range.

In 1914 I examined briefly a section at the summit of the Sawatch range, intermediate between Aspen and Leadville, or perhaps fifteen or sixteen miles distant in an air line from each. Here the pre-Cambrian granite of Aspen is found to be intrusive into older schists and gneisses, which make up a large portion of the range. Near Mount Champion this intrusive granite has the form of a rather regular dome, with the uplifted gneisses dipping away on all sides. In detail the granite is found to be intrusive into the gneiss, at the contact. Near the contact, partly in the gneiss and partly in the granite, are aplitic (alaskite) dikes, and at the summit of the dome are auriferous quartz veins of the deep-seated type found in the Appalachians and California. Gneisses, granite, aplitic dikes, and auriferous quartz veins are all pre-Cambrian.

Thus we have only two general periods of known igneous intrusion recognized in this section of the Sawatch range (comprising the Aspen and the Mount Champion districts),

[9] *Monograph* XXXI, U. S. Geol. Surv., p. 150.

the one pre-Cambrian and the other post-Cretaceous; and only two known periods of ore deposition, which are closely connected with the respective intrusions; in the case of the post-Cretaceous mineralization, a domal upgrowth of subjacent magma is inferred, and in the case of the pre-Cambrian mineralization, a domal upgrowth of the intruding magma is now exposed by subsequent erosion. The layering of the gneiss appears to be conformable on all sides to the surface of the granite dome, showing that the granite has bodily uplifted the gneiss cover, as is the case with the upper surface of a laccolith; but there is no evidence that it is a laccolith; it is a boss (or batholith).

In the Mosquito range, which lies east of the Sawatch, across the valley of the Arkansas, the sedimentary and pre-Cambrian formations are in general not very different from those at Aspen. Great quantities of siliceous igneous rock (alaskite porphyry and monzonite porphyry) have been intruded into the sedimentaries as sheets and intrusive masses, at the same general period as at Aspen—namely, at the close of the Cretaceous. Subsequent to the intrusions, numerous faults originated, which had a gradual growth, and in some cases became very large, with vertical elements of displacement amounting to several thousand feet. In the early stages of this faulting, ore deposition took place.

The evidence indicates that the blocks between the major faults were rotated or tilted by the faulting; and that these blocks rose, one behind the other, till the summit of the range was formed.[10] There appears to be no explanation of conditions other than that erosion has not yet counterbalanced the surface inequalities produced by faulting and tilting; and that to the faulting the relief of the Mosquito range over the surrounding country is directly due.

Summing up, the conditions at Leadville are strikingly

[10] I am somewhat familiar with Leadville geology, and my statements and conclusions, in so far as they are not founded on the fundamental data of Emmons' monograph, are the result of my own study and field work, as recorded in unpublished notes and reports.

similar to those at Aspen. There appears to have been no recognized faulting till after the immense intrusions; then the growth of the Mosquito range began, the uplift exceeding erosion so that a range of direct deformation has resulted, the uplift being accomplished largely by faulting, in the early stages of which ore deposition occurred.

What was this local, slow-moving, uplifting force? There is no evidence of lateral thrust; the movement is as if from an upward force exerted from directly below. The association of the locus of uplift with that of igneous rocks intruded just previous to the beginning of uplift suggests, as at Aspen, an uprising body of magma at the roots of the range.

South of the area which has just been discussed, the term San Juan region is applied to a broad mountainous tract in southwestern Colorado. The chief mountain mass, known as the San Juan Mountains, is a broad quaquaversal domal uplift,[11] which was formed during the general post-Cretaceous uplift. Several lesser domal uplifts, such as those of the Rico, La Plata, and Needle Mountains, have been superimposed upon or added to the larger San Juan structure, subsequent to its formation, and their growth has continued throughout the Tertiary. Intense igneous activity, resulting in magma being intruded as dikes, sheets, and laccoliths, and also extruded at the surface, followed the formation of the larger San Juan structure; but the growth of the lesser and later domes, such as the Rico and perhaps the La Plata dome, continued to a later period, and it appears certain that each of these domes was formed by a single uplifting force, acting independent of and subsequent to any observed intrusion of igneous rock. The San Juan structure, which is believed to have been an earlier and larger manifestation of the same force, was also probably formed by a force pressing upward from below and not represented by any

[11] The data concerning the San Juan region are taken from the published reports of Ransome, Spencer, Cross, Howe, and others. (U. S. Geol. Surv. reports.) In a general way, I am personally familiar with the region.

known intrusions.[12] The uplifting of the later and lesser domes, particularly, was accompanied by and largely accomplished by complex faulting; and also was accompanied by ore deposition.

What was the updoming force which repeatedly *and continually* exhibited its effects? The San Juan region is typically one of igneous activity, and the different products of eruption—the surface lavas, the stocks, the sheets and laccoliths—do not differ essentially in chemical composition from one another. The rock of the laccoliths is similar [13] to that of porphyry masses scattered through Colorado and adjacent parts of Utah, Arizona, New Mexico, and Mexico. An underlying magma basin of considerable importance is therefore indicated; and the minor domal growths, largely subsequent to the volcanic activity, may be assumed to be due to the upward pressure of slowly rising magma columns or domes. If that be the case, the column or dome which uplifted the main San Juan Mountains was so large as to be hardly a local affair, for this uplift is some 50 miles in diameter,[14] while the later and minor auxiliary domes are much smaller, although definitely larger than the dome at Aspen.

In Colorado, intrusions of rock which have been referred to this general early Tertiary monzonitic magma occur (as dikes, sheets, or laccoliths) in a broad northeast belt about 250 miles in length. The known intrusions of this monzonitic magma, however, appear not to be confined to this rude belt, for in the Spanish Peaks district[15] the eruption of a monzonitic magma in Tertiary time caused a great upward bulge, faulted at the summit, and associated with

[12] This is the general conclusion of geologists who have especially studied the San Juan structure, such as Cross, Spencer, and Ransome.

[13] There is a "consanguinity" or evident "blood relationship" between the rocks of this province, suggesting a common magma basin. Magma differentiation has produced great variations, but with this in view the general type and range of the rocks is found to be constant.

[14] *Professional Paper* 63, U. S. Geol. Surv., p. 128.

[15] Folio 71, U. S. Geol. Surv., 1901.

ore deposition. Other Tertiary centers of ore deposition connected with volcanism occur between the northeast belt above referred to and the Spanish Peaks, so that a map of the principal metal-mining districts[16] (Fig. 78) shows that they are inclosed in an isosceles right triangle of which the vertical side and the base are each about 200 miles long and the northeast trending hypothenuse is about 250 miles in length. Monzonitic eruptions are found at the three angles of this triangle (associated with the ore deposits); and it seems a reasonable assumption that the whole triangle is more or less underlain with the magma; and as the triangle comprises the main Rocky Mountain uplift of Colorado, it appears a reasonable working hypothesis that this uplift, which took place at the close of the Cretaceous, and progressed throughout the Tertiary, is due to a larger manifestation of the same vertical powerful uplift which produced the minor domal uplifts within its borders.

In point of magnitude it is a gradual step from the Aspen dome to the Rico and La Plata domes, and then to the larger San Juan dome, with a diameter of some fifty miles; and in all these cases a similar origin has been independently reasoned out; and it seems that the Rocky Mountain uplift in Colorado may well be a larger uplift of the same nature, on which all these domes are auxiliary.

I have indicated above that there is a general uniformity of igneous, dynamic, and ore-depositing phenomena over a wide area, embracing at least the Colorado region, parts of Utah, Arizona, and New Mexico, and of old Mexico as well—involving intrusions of large quantities of monzonitic magma at the close of the Cretaceous, or in the early Tertiary, with more or less attendant or genetically connected folding, faulting, and ore deposition. I shall touch upon a few districts in this great province, which we may term with justice a metallographic as well as a petrographic province, on account of the similar age and composition of the igneous

[16] *Professional Paper* 63, U. S. Geol. Surv., Plate XVIII.

rocks, and the similar age and composition of the ore deposits.

Near Matehuala, in the State of San Luis Potosi, in the north-central part of the Mexican Plateau, intrusive monzonite occurs in restricted areas. It has penetrated a massive blue limestone, which, with thick overlying shales,

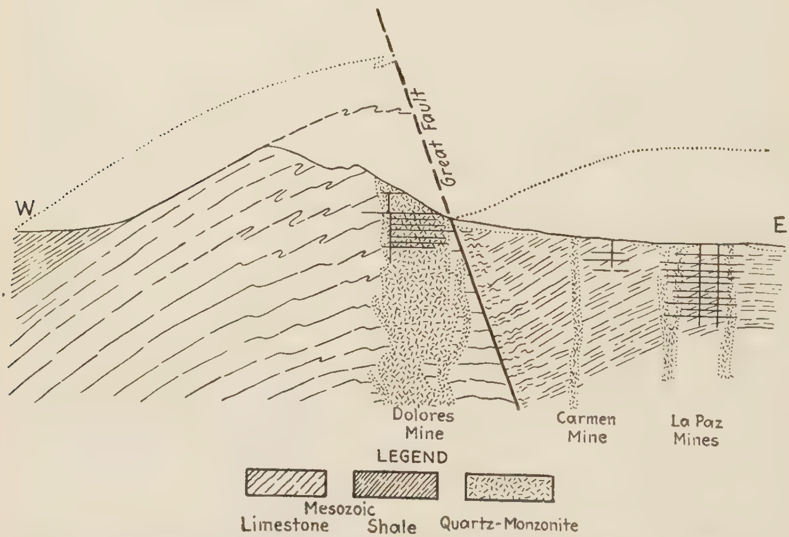


Fig. 45.—Matehuala, San Luis Potosi, Mexico. Vertical cross-section through the Sierra del Fraile. Shows domical uplift in sedimentaries, with igneous intrusion in center, the uplift on one side being taken up by an enormous fault. This fault is later, not only than the intrusion, but than the subsequent ore deposition. Scale 1 : 25,000. From Spurr, Garrey, and Fenner: "Econ. Geol.," Aug., 1912, Fig. 65.

is characteristic of all this portion of Mexico, and is of Mesozoic age, ranging from Jurassic through the Cretaceous. The intrusions are therefore believed to be post-Cretaceous. Around the intrusions the limestones have been sharply bent up into a halved dome, with a dip-slope on the north, south, and west, and an enormous normal fault on the east, which has a vertical displacement of at least a mile (Figs. 45 and 46).[17] Thus, an isolated moun-

[17] *Econ. Geol.,* Vol. VII, No. 5, Aug., 1912; Figs. 65 and 66.

tain, standing in the plain, is formed, called the Sierra del Fraile—the "Monk's Peak." Fig. 46 shows the position of the monzonite intrusions in the central field of the half dome, and also shows the suggested relation between the intrusion and the structure—as if the sudden bulge were due to the local upward pressure of the intrusion. Nevertheless, the proof is complete that the fault (Fig. 45), and consequently the dome, originated not only after the intrusion of the monzonite but after the series of phenomena of metamorphism and ore deposition which ensued; that it

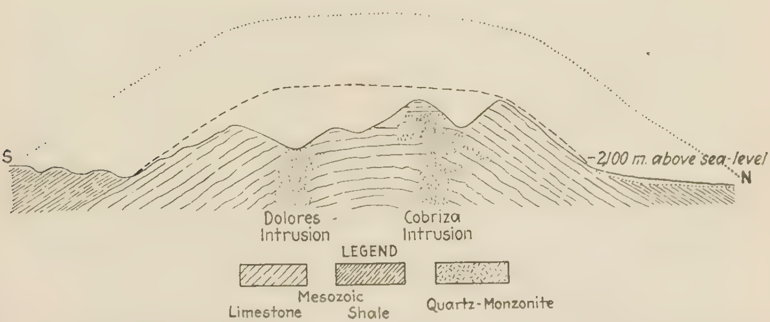


Fig. 46.—Matehuala, San Luis Potosi, Mexico. Longitudinal vertical section through the Sierra del Fraile, showing dome of sedimentary rocks, with igneous intrusions in the center. Scale 1:60,000. From Spurr, Garrey, and Fenner: "Econ. Geol.," Aug., 1912, Fig. 65.

originated at the very close of the vein formation, and has had its remarkable growth since then.

Study of the structure shows that this is not a case of a dome halved by subsequent faulting; there appears to be no corresponding structure on the other side of the fault Rather, the fault is one of the original boundaries of the uplift; some force, exerted vertically upward from below, has arched up the limestone beds, which broke away from the strata to the east along a jagged north-south fault. The two lines of evidence as to the origin of the dome—1, that it is probably connected with the monzonite intrusion, and 2, that it has formed entirely and distinctly subsequent to the intrusion—may be satisfied by the explanation

that the intrusive plug of monzonite which now outcrops was, after its intrusion, subject to the upward impulse of deeply buried unconsolidated portions of the magma column.

The growth of the dome and fault seems to have been gradual, and is probably still progressing, like the smaller faulted dome described above at Aspen; and, as at Aspen, I was led to the hypothesis that there was a rather close balance or equilibrium between uplift and gravity pressure; and therefore that uplift kept pace fairly well with the stripping off of weight by erosion from the dome.

A hundred and fifty miles north of this district in Mexico, especially near Monterey, the observer may see from the train many isolated mountains formed by this thick Mesozoic limestone series, and many of these mountains appear to have the dome-structure. Mitre Mountain, just west of Monterey, is a beautiful example of a sharp anticlinal dome. The higher domes are most dissected—the lower ones very little. No igneous rocks are exposed in these domes, so far as I am aware, but they are characterized by deposits of lead and zinc, indicating the possibility of igneous rocks in depth. Of these I am only familiar with the Zaragoza mine, close to Monterey, which shows irregular chimneys of lead and zinc sulphides, in limestone, without attendant igneous rocks. Since all our studies have shown, and as I will show more in detail later, the galena zone of deposition to be at some distance above the igneous source of mineralizing solutions, I have no doubt that the upward pressure of turrets of igneous magma from below is the cause of the formation of these local sharp domes.

Some two hundred miles west of Monterey and about the same distance northwest of Matehuala is the Velardeña district, in the State of Durango, where, as in Matehuala, I have made most detailed and prolonged geological surveys.

The San Lorenzo range, near Velardeña, which contains many important ore deposits of lead, silver, gold, and copper, is of limited size, the main portion being only a

few miles long, and less in width. In its present form the range is believed to be of recent growth, an "anticlinal range of direct deformation"—in other words, that the relief of the range is not entirely due to erosion, but largely to the growth of the dome structure in the rocks. This is indicated by the arching up over the range (where not removed by erosion) of a series of alaskitic tuffs and flows, which elsewhere lie horizontal. The heart of the range, laid bare by deep erosion (which probably went on before and during this last uplift) shows a series of large dioritic intrusions[18] into the characteristic thick limestones of Northern Mexico; the size of the range seems to have a relation to that of the known field of intrusion which occupies the center, although the intrusion, as at Matehuala, was earlier than the dome-shaped elevation of the present range, since the alaskitic volcanoes above mentioned have been proved to be of about the same age as the dioritic intrusions. There is in this range evidence of the gradual growth of a set of fault fissures with increasing openness; and the ore deposition, with its various successive stages, occurred, as at Matehuala, only during the early part of the period of movement along these faults. The displacement of the larger fault movements is such as to show that they assisted in the formation of the mountain dome; although, as above noted, much of the uplift appears to have been accomplished by gradual arching or flexing.

We have here, then, a sequence of geologic events and an apparent origin of the growth of an individual mountain dome, similar to that at Matehuala, if not so clean cut; and the growth of the range, being caused apparently by local upward pressure, may be believed to be due to the slow uplifting of unconsolidated magma far below.

Fifty miles north of Velardeña is the important mining district of Mapimi, where silver-bearing lead ores have been and are mined and smelted on a large scale. I and my

[18] These range from diabasic to granitic phases, as the result of differentiation.

assistants have made a most minute and careful geological survey of the mining district and the near-by territory, covering in all some twenty-five square miles. The Sierra de Mapimi, or the Bufa, as it is locally called, on one flank of which are the ore deposits, rises boldly and precipitously to a height of about 4,000 feet from the plain on three sides, except for ridges of foothills on the east; on the fourth side it diminishes in height and is extended to form a larger unit of the series of irregular mountains which rise from the desert plain, here and throughout all this portion of Mexico.

The bold steep fronts of this range, and the lack of any regular system of well-distributed deep drainage lines, would stamp the Sierra de Mapimi, in the eyes of a current school of physiographers who place physiographic (i.e., topographic) evidence as more reliable than geologic in cases like this, as a "young" range, recently uplifted. It is a typical "basin range" as the term has been used in geologic and physiographic discussions; as, indeed, are those described at Velardeña and elsewhere; and as such the school above mentioned would refer its uplift to recent faulting ("block faulting"), following the rut made by an unfortunate broad generalization made by our earlier American geologists in advance of detailed geologic examinations.

Our investigation, however, shows that the form of the mountain is due to folding: on three sides and a portion of the fourth, the limestone strata, of which the range is mainly composed, dip down in approximate conformity with the slopes of the mountain, beneath the recent desert valley detritus. This is the same heavy Mesozoic limestone series which we have noted at Velardeña and Matehuala; and, as at Matehuala, a thick shale series overlies the limestone, being found along the base of the mountain and in the minor infolded belts in the range, so as to show that not very much of limestone has been eroded. The general surface contour of the range follows the limestone-shale con-

tact. In a broad way, that is my impression of this whole region in Mexico, based on observations at various points: the Mesozoic shale series has been eroded from the top of upward protuberances of the limestone beneath, whether these protuberances are due to upfolding, or faulting, or both; and thus these are left as mountains, their irregular and varied relief being due primarily to their structure; while in the depressions of the undulating shale-limestone contact, the shale still remains, and has been largely covered by the spread-out detritus derived from the erosion of the hills. The actual relief of the ranges and mountains is then due in most cases to differential erosion: had the entire series been of shales, instead of the upper part being shale and the lower part more resistant limestone, none of these present features of relief would have been left.

The cross-sections of the range (taken across its shortest axis, from southwest to northeast) show a most interesting structure (Figs. 47, 48, 49). Although in general the dome is an open anticlinal uplift, dipping away from the center on three sides, yet this dome, in its highest and boldest part, is interrupted by close folding, which in some places is displayed in a single minor fold, as shown in the southwestern part of Section C (Fig. 47), or in a considerable belt as shown in the northeastern part of the same section. This belt runs from the north base of the mountain southeasterly up into the range; it is a broad slightly undulating syncline at the base of the range (Sec. A, Fig. 47), and becomes more compressed as the belt ascends into the range and comes opposite the highest part of the mountain (Sec. C, Fig. 47). Here, as shown in the section, the folds are compressed and typically are overthrown to the northeast, on the southwest side of the close-folded belt, or away from the main mass of the mountain; while on the northeast side of the close-folded belt the tendency is for the folds to be overthrown to the southwest, or toward the main mass of the mountain. Locally, there has even been a little overthrust faulting (shown in this section, and in Sec. D

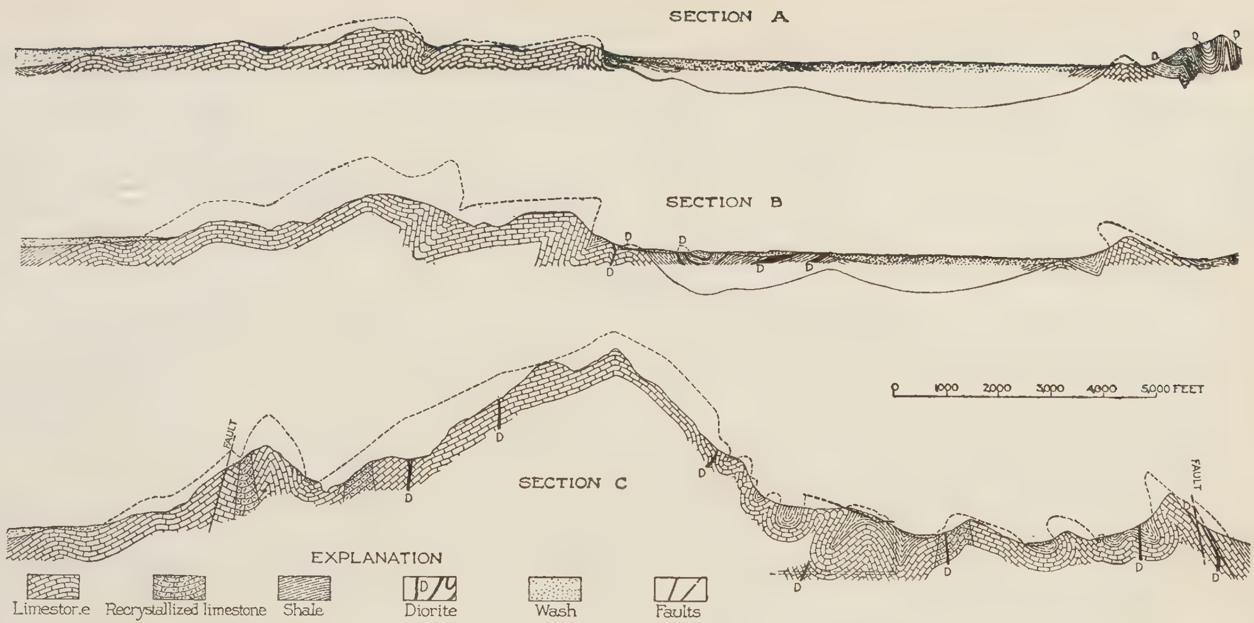
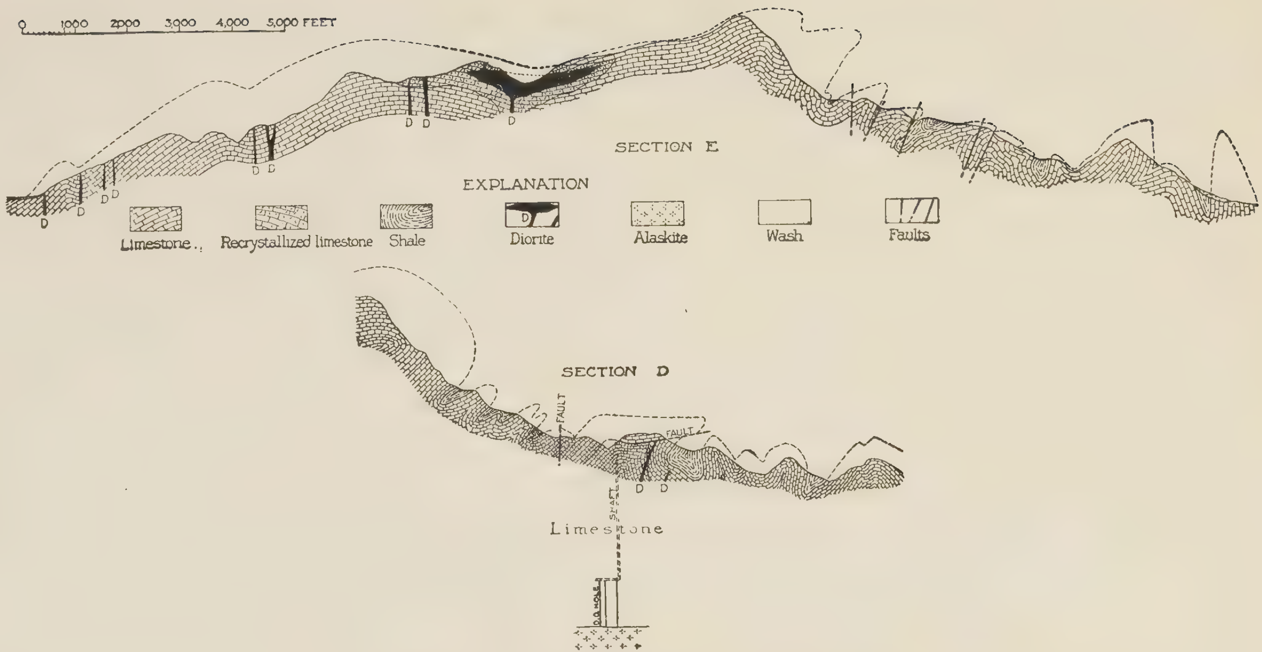


FIG. 47.—Mapimi, Durango, Mexico. Geological cross-sections across the Sierra de Mapimi. Sections A, B, C. The sections run from northeast, at the right-hand side, to southwest, at the left-hand side; accordingly, the reader is looking to the northwest. Sections A, B, and C are parallel, A being farthest northwest, and C farthest southeast, while Section B lies in between. Successively southeast of Section C lie Sections D, E, F, and G (Figs. 48 and 49). All the sections are taken across the shortest axis of the range. Continuous line of dashes in each section shows main limestone-shale contact, actual or restored. Spurr, Garrey, and assistants.



S.W. N.E.

FIG. 48.—Mapimi, Durango, Mexico. Geological cross-sections across the Sierra de Mapimi. Sections D, E. Continuous line of dashes in each section shows main limestone-shale contact, actual or restored. Spurr, Garrey, and assistants.

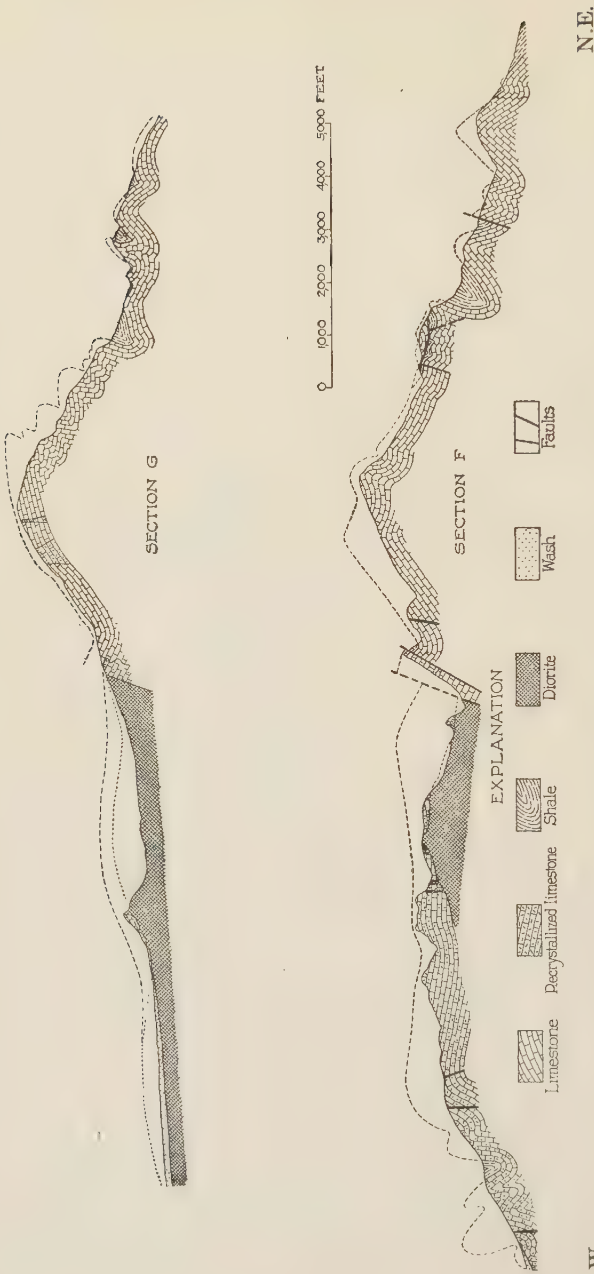


Fig. 49.—Mapimi, Durango, Mexico. Geological cross-sections across the Sierra de Mapimi. Sections F, G. Continuous line of dashes in each section shows main limestone-shale contact, actual or restored. Spurr, Garrey, and assistants.

[Fig. 48]), producing on the southwest side of the belt a horizontal over-ride eastward of the limestone over the shales, totaling from 600 to 800 feet on Ojuela hill; and on the lower or northeast side of the belt a slight probable overthrust in the reverse direction was noted in one section, amounting, it is reasonable to assume, to not more than 200 feet.

If, as is commonly taken for granted, closely appressed or overthrown folds are the result of lateral pressure, and the direction whence the pressure has been applied is indicated by the direction in which the folds are overthrown—i.e., the axes of the overthrown folds dip toward that direction of the compass whence the pressure has come—then these local belts of close and overthrown folding have not come from a single pressure, but from distinct ones, coming from different directions. In the main close-folded belt described above, the heaviest folding has been due to a thrust from the direction of the mass of the range; while on the other side of the belt a strong and persistent pressure must have come from exactly the opposite direction. The two sets of rock folds or waves met in this zone, and the resultant structure is strongly suggestive of the "chop sea" which results when two sets of waves on the surface of water clash.

Let us note again that the maximum of close folding in the belt under consideration is opposite and on the flank of the highest part or the center of the dome uplift of the mountain, which is the predominant mountain structure, on which these close and overthrown minor folds are details; therefore, a genetic connection between the two types of folding—open dome-shaped uplift, and auxiliary close or overthrown folds—is suggested, and a common age and origin for the two is indicated.

If we consider the close and overthrown folds by themselves, with the very minor and local overthrust faulting, the local nature of these folds, and their diverse inclination, points, as above noted, to distinct centers of pressure, push-

ing from different directions. These pressures were effective and powerful, however, each in its restricted field: as shown in Section C, the main belt, which is now about 2,800 feet wide in this section, has been shortened from almost exactly double that amount. Were this structure regional, and characteristic of the whole formation in this section, we would be inclined to entertain the hypothesis of general crustal shortening due to shrinkage of the earth's crust, from any of the various physical causes which have been assigned for close and overthrown folding elsewhere—contraction due to emanation of volatile constituents, loss of heat, etc.; but the structure is not characteristic of the region or this formation in general; rather, as I have described, the general structure is an open and undulating one, and the indications and effects of this compression and crustal shortening are very local. Nor is there any evidence of a local belt or belts of weakness in these rocks, such as might bend and be compressed locally as the result of transverse compressive strains transmitted and accumulated from afar; the uniformity and great thickness of the underlying limestones and of the overlying shales preclude this hypothesis. Local forces, therefore, have shortened the crust of the main compressed belt in the section by 2,800 feet—and, as above noted, one of them was probably the same as that which has produced the very local and abrupt towering dome. Only one possible cause can be assigned: the intrusion of igneous masses. The main domical structure shows that the principal movement of this intrusive mass was from below, and the direction of thrust as indicated by the close-folded belt on the northeast flank of the main dome (Sec. C, Fig. 47, and E, Fig. 48—it is even more pronounced in Section D, Fig. 48) indicates a movement from the southwest.

Therefore the local intrusion which formed the dome moved upward diagonally, from the southwest, under the dome.

We may even approximate the general angle of move-

ment by comparing the vertical and horizontal elements. In Section C, Fig. 47, for example, I have measured a distance of 2,000 meters along the shale-limestone contact on either side of the summit of the dome uplift, following the curves of this contact. Rough measurements show that the summit of the dome has moved vertically up about 650 meters and to the northeast 225 meters to arrive at its present position from an original flat-lying attitude of the strata, assumed to be that of a straight line now connecting the two ends of this flexed 4,000-meter traverse along the present contact. These two components give an angle of about 70° from the horizontal, up and toward the northeast, as the direction of movement.

Similarly, on Section B, Fig. 47, taken across the northwest-pitching slope of the mountain dome (along a northeast-southwest line, parallel to Section C, and two miles northwest of it), a similar measurement of 2,000 meters on each side of the summit of the dome indicates that the summit of the dome has moved vertically up 550 meters and to the northeast 250 meters, indicating an angle of uplift of 65° from the horizontal. On Section G (Fig. 49) the furthest southeast section made and over three miles southeast of Section C, a distance of 1,250 meters measured on each side of the summit of the dome along the shale-limestone contact shows a vertical elevation of 650 meters, and a horizontal migration to the northeast of 225 meters, which combine into a general angle of movement of 70° from the horizontal, up and over to the northeast. This agreement on the different sections, showing, as the illustration indicates, quite different folding in detail, is very striking, and indicates clearly that the intrusion which was responsible for both doming and close folding of the main dome moved up from below to the northeast at an angle of 65 to 70° from the horizontal. That it was a body or column of limited horizontal extent is shown by the sharp limitations of the dome and of the mountain boundaries, and it may have been either a laccolithic accumulation in

the limestone strata below, a batholithic dome-like protuberance, or a plutonic plug.

In the close-folded beds shown at the northeast end of Sections A, B, and C, forming the northeast side of the close-folded belt of Section C, we have, however, as above noted, evidence of a distinct pressure from that which caused the main dome, and one whose horizontal component of movement was opposite to that just described, being toward the southwest. This must be assumed to have been caused by a different intrusion in the field beyond the mapped area.

Having reasoned out these conclusions, let us examine the known igneous rocks of the mountain; for this section, and indeed all this region of Mexico which we are discussing, has been the scene of post-Cretaceous and Tertiary igneous intrusion and volcanic action. For the purposes of discussing the structure of the Sierra de Mapimi, it will be best to confine ourselves to that part actually mapped, and to illustrate our discussion by the cross-sections.

Two types of igneous rocks are encountered in the range—diorite and alaskite. The diorite is shown in Sections E, F, and G—on the southwestern flank of the mountain. The alaskite does not outcrop in the range, although it is intrusive into it; only the top of the intrusion has been found in drill holes at a depth of about 1,505 meters (3,400 feet), at the northeast base of the mountain (Section D). The outcropping of this alaskite intrusive was noted seven miles to the north, where alaskite porphyry intrudes the shale series.

Was the doming and folding due to either the diorite or the alaskite intrusion—or to both?

The main belt of ore deposition is in the close-folded belt described at the northeastern base of the mountain. The belts of mineralization trend with the close folding, and the ores have an evident relation to the individual folds, being deposited in many cases along the axes of the anticlines or synclines. Therefore, the ore deposition was later than the

folding. This ore deposition is shown by many indications to be dependent on and to have followed the alaskite intrusion found in depth. On the other hand, all veins stop at the diorite dikes and also at the larger intrusive masses of diorite, showing that the diorite is younger than the ores. Moreover, the diorite dikes in the closely folded area have in many cases followed, like the mineralizing solutions, the weak axes of appressed synclines and anticlines (Fig. 154). Therefore the diorite was introduced into the mountain *after* the formation of the slightly asymmetric and plicated dome, and cannot have been the cause of it. The alaskite intrusion may have caused the uplifting and attendant compression, in which case the alaskite extends under and to the southwest of the range, at still greater depths; or the deforming impulse may have been due to a still deeper magma body, not discovered. The position of the large diorite intrusions on the southwest flank of the mountain, or on the side whence the transverse element of the folding pressure came, would have led to the assumption that the folding was due to this diorite intrusion, did not the facts negative this conclusion.

Both diorite and alaskite are types that are common to this portion of Mexico. At Velardeña, as described above, the diorite intrusions of the San Lorenzo range are *earlier* than the updoming of the range, as well as the ore deposition. At Peñoles, a short distance (thirty miles) from Mapimi, is a hornblende diorite similar to the hornblende diorite in the Sierra de Mapimi, intrusive into the same or a similar limestone series; and here the diorite, as at Velardeña, was intruded *previous* to all ore deposition.

It is therefore a very permissible hypothesis that the upward-moving mass which caused the dome at Mapimi may, after all, have been of diorite; and that the intrusive masses now exposed by erosion on the southwest flank of the range may have been later emissaries sent from the same source. Studies at Velardeña show that all these igneous rocks are probably the result of differentiation from

a general dioritic or monzonitic magma: in the San Lorenzo range, diabase, diorite, and granite, and presumably also alaskite, had a common derivation. At Matehuala the intrusions show phases from diorite to granite, developed as the result of differentiation in the same intrusion. Therefore at Mapimi both diorite and alaskite may be derived from a single local magma body, whose upward and lateral pressure was the cause of the domal uplift and compression.

It is to be noted that a dome may be formed *before* intrusions which are exposed at the surface, as at Mapimi; or *after* such intrusions, as at Matehuala and Velardeña; or without any demonstrable (i.e., shallow) intrusions, as near Monterey. Plainly the doming impulse may come from slow upward intrusion at considerable or great depths, with or without minor intrusions, which, when in evidence, may take place at any stage into the shallower crust. *The domical type of structure, then, and not the presence or relative age of intrusive rocks, is the criterion of magma surgence.*

The diorite intrusions on the southwest flank of the Sierra de Mapimi have a nearly flat top, as shown in Sections E, F, and G (Figs. 48 and 49). The uppermost outcropping body shown in Section E has a flat top and is noncontinuous to the southwest. It has not pushed up the strata above it, and hence may be assumed not to be thick. These characteristics denote a small laccolithic body.

The mass shown in Sections F and G outcrops separately from the one in Section E, occupies the southeastern corner of the mapped area, and is of unknown dimensions; but it is certainly connected with the near-by outlying small intrusion of Section E (Fig. 48). The character and contour of the top of this larger intrusion where it comes in contact with the limestone above show that it had a rolling, generally flat surface, which extended nearly up to the shale contact. Inspection of the restored shale-limestone contact above the diorite mass (and the diorite dike area, which, in Sections F and G, evidently points to an extension

of diorite at no great depth below) shows a local upward doming above the diorite intrusion, probably corresponding, as indicated by Section G (Fig. 49), with the upward bulge of the upper surface of the diorite, and probably caused by the intrusion. The gentleness of this uplift suggests that this large diorite mass is also a laccolith, like the smaller one shown in Section E. On the southwest end of this local upswelling on the west flank of the range there are, as shown in Section E, some minor corrugations of the strata, which in Section F have become a zone of fairly close folding, overthrown to the southwest, or away from the range, and away from the highest bulge of the diorite in this section. A horizontal element of movement to the southwest, attendant on the main vertical movement consequent upon the intrusion, is indicated.

This local dome, then, on the flank and at the base of the main Sierra de Mapimi dome, is of later origin than the main dome.

I have dwelt particularly upon the structure of the Sierra de Mapimi and its origin, because it is a key occurrence, taken together with the other Mexican examples cited; and because it has been mapped with the utmost care and accuracy over a very considerable area. I believe we learn more of the broad principles of geology by intense study of the actual lessons yielded by certain examples than by generalization and theories derived from a study of maps of large areas and our own notions concerning what may have happened or what may be happening in the earth. Our investigations of the Sierra de Mapimi explain the probable origin of the irregularly shaped and distributed, often dome-like mountains of this section of Mexico, as due to the force of intrusion of domes or fingers or belts of magma slowly moving upward during a vast period of time—during the whole Tertiary and down to the present, in repeated intrusions which solidified in depth, or in certain places and at certain times resulted in outbreaks of lava at the surface. Moreover, the interpretation of the Sierra de

Mapimi shows that close and even overthrown folds, and even overthrust faults, may be due, locally and on a small scale, to the horizontal element in local igneous intrusions or diagonally upward magma migrations. We may, therefore, bear it in mind that overthrown folding on a larger scale may in some cases be due to a similar diagonally upward magma migration of larger dimensions; and the same may be true of overthrust faults.

The general similarity (more intelligibly, perhaps, the recurrence of the same types and the evidences of consanguinity and common origin by differentiation of all) of the igneous rocks described at these Mexican localities suggests that in depth these rocks may form and have formed a part of a single magma basin of an intermediate (dioritic or monzonitic) composition; just as the inferred conception of the nature of these intrusions as upshoots or advance guards also connotes a larger mass below; and just as the great dome-shaped or batholithic granitic intrusions described in the pre-Cambrian in Colorado and Canada characteristically indicate further expansion in depth. This Mexican magma is similar in general composition to that noted in Arizona and Colorado as having accompanied (and probably, I believe, caused) the crustal uplifts of Tertiary time and down to the present.

In all these Mexican examples intrusion was not *permitted* by folding and faulting due to the earth's adjustments attendant upon shrinkage, according to a current theory which I have previously cited; it was due to the telluric force residing in the magma, which, being patiently and persistently applied, was able to uplift, punch up, and hold up the immense weight of overlying rocks, at many separate points. Such a gigantic force, if far in excess of the gravity pressure of overlying rocks, would impel the magmas strenuously to the surface, where they would arrive explosively; and the surface volcanics of the region are a record of such episodes. Otherwise the evidence as to intrusion of portions of the magma which have not reached

the surface is that it moved and is still moving upward very slowly, and that the telluric pressure is in places in equilibrium with the gravity pressure of the overlying rocks, so that the magma movement and the uplifting keeps pace with the lightening of the surface load by erosion.

If volcanic outbursts in this magma field have been evidence of excessive telluric pressure in the magma, their cessation points to the relief of this pressure by the outbreaks; and the recurrence at intervals of volcanic activity points to the growth and increase of telluric pressure when these openings are sealed. We may assume that these centers and lines of outbreak tend to lessen the telluric pressure for the whole magma body, basin, or sea whence they are derived. Therefore, the period of least general telluric pressure in the magma in depth will be immediately succeeding a period of eruption; that of the greatest telluric pressure the period immediately preceding a period of outbreak. In the latter case, with a given weight of overlying rocks, the telluric pressure will tend to uplifts which are more rapid than erosion; and in the former case uplifts may pause, or the weight of the rocks may exceed the telluric pressure, causing subsidences. Periodic up-and-down movements, or oscillations of the crust, would thus be caused. Such oscillations are characteristic of the known continental crust, both in the area I have been discussing and elsewhere; and a characteristic uplift previous to volcanic outbursts and a partial subsidence which follows them have been demonstrated from both local and regional studies, to which I shall refer later.

Whether these oscillations in volcanic fields, and evidently both antecedent and subsequent to volcanic outbreaks, are of the same nature as certain broader and even continental oscillations, is a question; I think they are, as they are of the same order and approach the same degree of magnitude.

In a region like this Mexican province, which shows the local uplifting force of many separate and distinct upward-

struggling small intrusions, what of the uplifting force of the broader magma fields in depth? The hollows between these local uplifts are not crustal depressions—the whole region has been uplifted, and the plains between the local uplifts stand thousands of feet above the sea. Is not this the result of being uplifted and upheld by the larger magma body in depth? But this, you will say, is a part of the Mexican Plateau, that broad uplift which embraces most of Mexico, and falls away steeply on the east and west to the Gulf of Mexico and the Gulf of California and the Pacific. Precisely: the Mexican Plateau is to my mind indicated as having this origin, and the Mexican Plateau is only a part of the continuous broad northwesterly trending plateau and mountain belt which runs north through Arizona and New Mexico to Colorado and Utah, the Colorado portion of which has already been suggested as a domal uplift due to the pressure of upwelling magma. The extent of this plateau is, of course, still greater, comprising a large part of North America from the Rockies west.

In the Rocky Mountain region and westward, examples of the dome structure are frequent. Many of these are connected with and due to igneous intrusion, as has been shown by Gilbert and by Cross for those domes whose upbending is explained by the laccoliths which occupy their cores; while the Uintah range, in Utah, a typically perfect local domical uplift, shows no igneous rocks, its exposed core being of Paleozoic strata. This is probably due to the upward pressure of a batholithic dome or a plutonic column or plug below.

A relief map of North America shows the main uplifted belt I have described as passing from Mexico, through New Mexico and Arizona, Colorado and Utah, continuously up through Canada and Alaska. From Mexico City into British Columbia the Rocky Mountain belt is fairly straight, but the Sierra Nevada Coast Range uplift is a decided and fairly regular curve, an arc of which the Rocky Mountain belt is the chord, a segment having its greatest width oppo-

site San Francisco, and its ends in British Columbia and near Mexico City. Within the United States, part of this inclosed segment has been commonly called the Great Basin. This name is somewhat misleading, as this segment is of diverse nature and origin. A great part of it is ribbed with narrow minor mountain ridges, of no great length or width, but of considerable height. East of this mountain region the rocks are not folded, and through this unfolded region the Colorado River flows. This Colorado Plateau, as it is called, is not commonly included in the Great Basin, but it is a part of the segment I have in mind; it is elevated several thousand feet above the sea. But the larger part of the mountain-ribbed segment is also a plateau of corresponding height, the desert plain, cut up into broad valleys by the rows of mountain ridges, being for the most part several thousand feet above the sea level. I will call this the Nevada Plateau.

The ridges and mountains which rib and dot the surface of the Nevada Plateau are analogous to those which interrupt the plane of the Mexican Plateau, which is indeed continuous with the Nevada Plateau, through the similar Arizona-New Mexico plateau section, which is, again, a mountain-ribbed desert plateau, similar to that portion which lies in Nevada.

Many indications show that this great continental swelling has continued up till quite recently, and is still in progress. In arid regions like the main part of the Nevada-Arizona-Mexico plateau, this may not be evident for the whole broad uplift, although indicated, as I have mentioned, for some of the auxiliary domes; but in areas of considerable rainfall, where permanent streams exist, it has been noted in different places that streams cut across the uplifts, showing that these have developed during the life of the present streams, and so slowly that the downcutting of the streams was more rapid.

Some of the ranges of Nevada and Arizona appear to be local domal uplifts, like those I have described in Mexico.

Like the Mexican Plateau section, the Nevada-Arizona region is one which has undergone repeated and probably continuous folding and faulting during the whole period from the Jurassic to the present, contemporaneous with repeated igneous intrusions and extrusions (volcanic outbreaks); and the occasional definite mountain domes represent the more recent and the more restricted of the local upbendings. Most of the desert ranges, however, are older; and have been so affected by profound erosion that, whatever their structure, their present relief is due to differential erosion, which has left the more resistant rocks in relief. The rocks of these ranges, like the corresponding rocks of the intervening valleys, are folded and faulted. Local recent relatively rapid upswellings doubtless occur through the whole area, being accomplished both by upflexing and upfaulting; but the predominant differential erosion factor renders it difficult to disentangle this recent uplift factor, where it exists.

The above summary applies in general to the Nevada-Arizona-Mexico ridges. In Nevada, however, I find two very distinct and sharply marked fields or sets of ranges, which may be seen in the map accompanying my paper on the Basin Ranges.[19]

The larger field comprises the greater part of Nevada, and part of adjacent Utah. Here the ridges correspond with the summary above; they have long been exposed to erosion, and therefore are in many cases comparatively subdued; they have a north-south trend, in part slightly southwesterly.

The second field lies southwest of the main Nevada field and trends northwest and southeast, constituting a relatively narrow belt immediately adjoining, to the east, the main Sierra Nevada east-facing frontal scarp. In general, this belt shows bolder ranges than the larger belt, and deeper valleys between; the valleys, indeed, constitute, as a whole, the eastern slope of a general trough formed by the junction

[19] Geol. Soc. Am., Vol. XII, p. 266, 1901; Plate XX.

of the Nevada Plateau with the east base of the Sierra Nevada. I believe these mountains and valleys to be partly of distinct and later origin than the Nevada ranges, across whose trend this Sierra back-trough cuts diagonally; and I find their relief to be due largely to crustal movements: they are predominantly mountains and valleys of direct deformation, while throughout most of the Nevada Plateau, the mountain and valley relief is predominantly due to erosion. Speaking more accurately, this belt is a portion of the Nevada Plateau (with the common inheritance of complex movements and intrusions), which in relatively recent geologic time (contemporaneous with the general plateau tilting, and the uplift of the giant Western North American continental dome with its auxiliary swellings) has had superimposed on it very distinct local crustal uplifts and depressions. This is evidently the case, for example, with Death Valley, a long, narrow, northwest-trending depression which lies between abrupt ranges, and whose lowest portion, for many miles, lies below sea level (as much as 274 feet). Basin-like depressions similar to that in the bottom of Death Valley occur at various places in this belt, and although not below sea level, are evidently due to relatively recent crustal sinking. Some of them receive sufficient drainage from the Sierra Nevada to be turned into lakes—Owens Lake, Walker Lake, and Lake Mono.

Close geologic study has not gone far enough to enable me to state definitely what proportion of the depression of the valleys of this belt and the elevation of the ranges is due to flexing and what to faulting, but both have probably operated. The straight and abrupt east face of the Sierra Nevada has long been supposed to be due to uplift along a great fault, and I accept this conclusion; and it is very possible that many of the minor ranges of this Sierra back-trough belt may owe their relief, in part at least, to the same cause. Nevertheless, the doming and hollowing by flexing have been important, and perhaps predominant. In the Silver Peak range, Tertiary beds are arched up over the

lower portions, but do not reach the highest parts, pointing to a domelike uplift, in late Tertiary or post-Tertiary time, of a pre-existing range.[20]

The cause of the domal upgrowth of these ranges, which are in large part of volcanic origin, I assume to be the same as that suggested for the Sierra de Mapimi, in Mexico; the San Juan dome, in Colorado, and other domal uplifts: the upward pressure of upshoots of magma at their bases.

The geologic history of this belt of recent crustal disturbance, of local uplift of ranges and depression of valleys, with the net result that the valley system forms a depressed trough at the east base of the Sierra Nevada, shows that the belt has long occupied the same relation to the regions to the east (the Nevada Plateau) and to the west (the Sierra Nevada) that it does now; in fact, this belt has been subject to repeated depressions, as the Sierra Nevada has been subject to repeated corresponding uplifts, since the close of the Jurassic. Geologists who have worked out the history of the Sierra Nevada have proved that the close folding and shearing of the earlier sedimentary rocks took place at the close of the Jurassic or the beginning of the Cretaceous, and was contemporaneous with the great intrusions of granodioritic rock which are now exposed all along the eastern side of the range. The rocks were compressed into a great series of slates and schists, which as a rule dip easterly. The apparent monocline which this dip indicates has been explained[21] as a series of closely appressed and overthrown folds, the tops of which have been truncated. This prevailing easterly dip has been a source of perplexity to those geologists who see in the east-dipping overthrown folds of the Appalachians evidence of a horizontal thrust against the continent block from the direction of the Atlantic, and who therefore, on the assumption that the Sierra Nevada has been formed in an analogous way, would expect to find west-dipping overthrown folds characterizing it,

[20] *Professional Paper* 63, U. S. Geol. Surv., p. 55.
[21] Le Conte: *Am. Jour. Sci.*, 3d Series, Vol. XXI, p. 101.

indicating a thrust from the direction of the Pacific.[22] Let us consider, however, the amount of compression, of thrusting to one side, of the pre-Cretaceous sedimentaries, which must have been effected by the great belt of intrusive granodiorite which runs throughout the whole of this Sierra Nevada province, and the amount of upward flowage necessary for the adjustment by vertical expansion of the horizontally compressed rock; and we can understand that the folding and the schistosity both were probably accomplished by the telluric pressure of the great intrusive ridge, and that the general direction of folding and schistosity depends on the direction of the intrusion.

Phases of this granodiorite intrusion are now exposed, not only in the Sierra Nevada but in those adjacent minor ranges of California and Nevada which lie east of it. The sedimentary rocks of these ranges are found to be folded and faulted: in the White Mountains, Walcott found the chief fold in the intruded strata to be a syncline closely compressed and overthrown to the east. In the Spring Mountain range, which lies just east of an intrusive granitic area, Rowe [23] showed the existence of a heavy faulting overthrust to the east. East of this general belt which borders the Sierrá Nevada, as the granodioritic intrusions of this period disappear, the close folding also dies out.

The general overthrow of folds to the west, west of the main granodioritic axis of the Sierra Nevada, and the instances of overthrow to the east, east of this axis (as noted in the White Mountains and the Spring Mountain range), would indicate, as already concluded, that the thrusts came from the main Sierra Nevada intrusion against the rocks east and west.

As above noted, the late Jurassic early Cretaceous Sierra Nevada granodiorite intrusion and accompanying uplift created the Sierra Nevada ridge and determined the relatively lower position of the country east of it. During

[22] GEIKIE, JAMES: "Mountains, Their Origin, Growth and Decay," 1913.
[23] Bulletin 208, U. S. Geol. Surv., p. 177.

the late Eocene there were laid down in this relatively depressed area extensive lake beds; the trough apparently extended at that period, as at present, southeastward into the Mojave desert and Mexico. During the Miocene this same area was depressed, and was in part occupied by a lake which King called the Pah-Ute Lake, which covered much of Nevada, Idaho, eastern Oregon, and part of California. During the Pliocene, also, this trough still persisted, as shown by the area covered by the great lake of that period, the Shoshone Lake of King; and so on through the Pleistocene down to the present. The shifting of position of these successive Tertiary sets of lakes shows active warping, which went on throughout the Tertiary. The depressions occupied by the lakes were plainly crustal, and though they were part of the Sierra Nevada back-trough, they were, throughout the Tertiary, cut off from drainage southeasterly into the sea, as they are at present.

While the Sierra Nevada back-trough belt was subject to repeated irregular warpings and depressions from the Jurassic to the present, the Sierra Nevada range was subject to repeated uplifts, the plane of differential movement being the fault zone at its eastern base. The uplift of the Sierra Nevada at the close of the Jurassic was renewed at the close of the Cretaceous, resulting in a lofty range[24] which must have attained great elevation as compared with the back-trough at its eastern base.

Lake beds which do not extend past the present Sierra Nevada scarp show that scarp to have existed throughout the Tertiary period. Mr. Diller has further described Pleistocene faults along this scarp, one at Honey Lake having 3,000 feet vertical displacement; and recent movements have taken place along it. This faulting was not even, but was recurrent; and, gradual as each movement might appear when measured in terms of our experience, yet in relation to the whole history of faulting it was spasmodic.

[24] J. S. Diller: *Fourteenth Ann. Rep.*, U. S. Geol. Surv., Part II, p. 432.

Following the first Sierra Nevada uplift (at the close of the Jurassic) there was, then, a general uplift at the close of the Cretaceous, after which erosion appears to have outstripped the net sum of uplifts for a long period. Toward the close of the Eocene, deep lake basins were formed, as above stated, in the Sierra Nevada back-trough, and these were bounded on the west by a high wall along the eastern face of the Sierra, signifying a probable major uplift of the range at that time. Following this, there is evidence of the gradual development, in the Sierra Nevada, of a topography of little relief, of broad valleys and sluggish streams, the development of which appears to have reached its maximum in the Miocene.[25] In the Pliocene, uplift of the range outstripped erosion, and at the close of the Pliocene there was a great elevation, which would seem to have been renewed at frequent intervals down to the present. This evidence of spasmodic growth (I will not call it periodic, as I do not here infer any order or rhythm) of the Sierra Nevada uplift is important in considering the origin of mountain ranges, of continental units, and of continents, and I shall recur to it later.

If the Sierra Nevada has been uplifted at intervals along the fault scarp at its eastern base, ever since the close of the Jurassic, we have a most persistent fault block of continental-unit dimensions, which has been repeatedly pushed up by some force at its base, acting in large measure vertically from below. In a large way, the Sierra Nevada is analogous to the miniature example of the Sierra del Fraile at Matehuala; and we can conceive of no force in either case capable of producing the repeated uplifts except an ever-present (though constantly varying in intensity) upward pressure at its base.

Had we not already a sufficient clew to the nature of this force, we could reason it out afresh for the Sierra Nevada. What other great geologic event did the beginning of uplift coincide with, and what activity has since gone on, like

[25] J. S. Diller: *Fourteenth Ann. Rep.*, U. S. Geol. Surv., Part II, p. 421.

the upheavals, from the close of the Cretaceous to the present? It was the intrusion, on a continental-unit scale, of granodioritic magma and its derivatives at the close of the Jurassic, and the recurrent igneous activity, manifested by extrusions and intrusions, has kept up ever since. The great Pleistocene cones of Northern California, Washington, and Oregon (Shasta, Hood, Rainier, etc.) are silent; but in Alaska, they are active, and in California at least one—Mount Lassen—has spoken in recent years. The pressure at the base of the Sierra is then that of the body of magma, which has sent up offshoots from the close of the Cretaceous to the present.

Small-scale occurrences enable us to understand more readily large types; and the uplift of the Sierra del Fraile (p. 198) along a fault at its base enables us to understand the force which has uplifted and is uplifting the Sierra Nevada. So, as a side light on the recurrent and spasmodic periods of movement along the Sierra Nevada fault zone, we may consider a smaller example which was worked out at Ray, Arizona, by myself and assistants.

The rocks in the Ray mining district have at the base a complex series of schists of both igneous and sedimentary origin, which after uplift and an immense period of erosion was covered by Paleozoic quartzite and limestone. Probably near the close of the Cretaceous, a great dome or batholith of granite porphyry worked upward into the schists, and ore deposition (of disseminated primary lean copper-bearing sulphides, which later were to be concentrated by surface waters to form the ore deposits now worked) followed. (Fig. 50.)

Tertiary land deposits overlie the Paleozoic sediments, so that this was a land surface during the Tertiary, and perhaps long before. Desert wash deposits alternate with lava flows and accumulations of volcanic ash; and the last deposit, of Pleistocene age, was also a desert wash deposit.

Directly subsequent to the ore deposition, the first strong faulting occurred, especially along a great nearly vertical

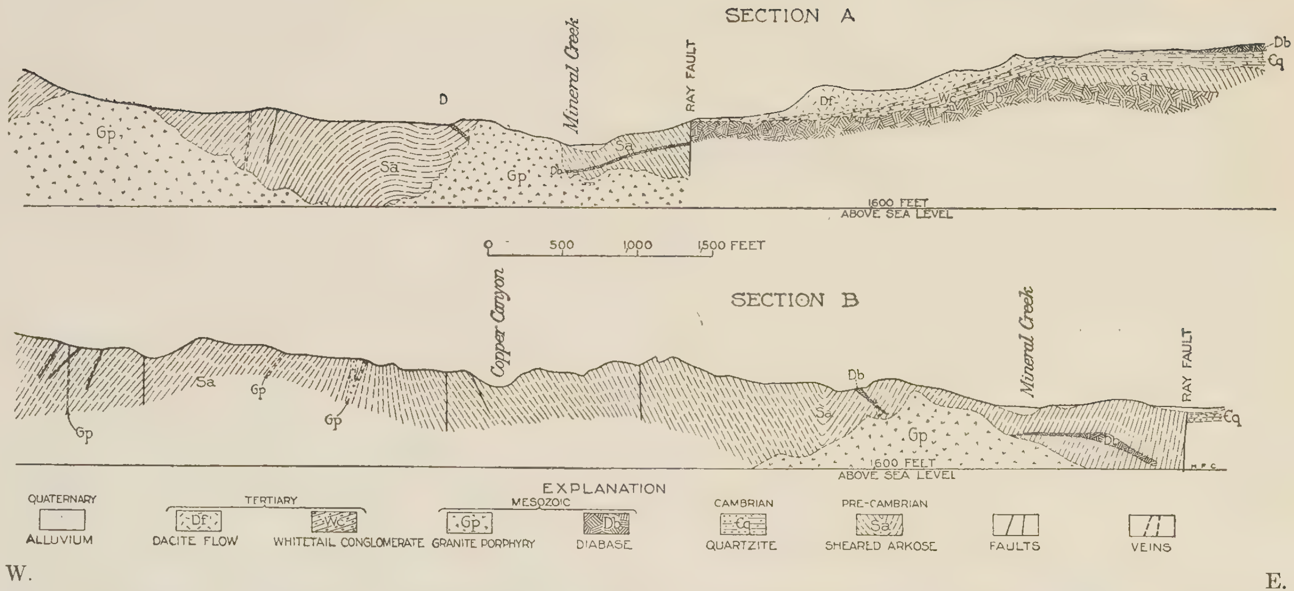


FIG. 50.—Sections through the Ray Consolidated copper mine, showing geological structure. Shows especially portions of the granite batholith (as actually determined from numerous drill holes); also, the Ray fault. The primary ores are disseminated in the schists and in the granite, and the commercial secondary copper ores are concentrated from them in a blanket not far below the surface, in these same rocks. These sections go through the disseminated ores; but the latter are omitted, so as to bring out the rock structure more clearly. (See Fig. 85.) The sections, which are parallel, run from east to west; and the reader is therefore looking north. By J. E. Spurr and J. H. Farrell.

fault (the Ray fault) which cuts north and south through the mineralized district; and the district occupied by the present major mining operations on the west side of the fault was uplifted, relatively to the country on the east side, perhaps one or two thousand feet. Erosion attacked the uplifted block and reduced it to the level of the other block, and Tertiary deposits of lava and desert wash were laid down upon the leveled country. Again, at about the end of the Tertiary, the same block (west of the Ray fault) was once more powerfully uplifted, probably upward of a thousand feet, and the uplifted area was again attacked by erosion, and the Tertiary rocks were stripped off. Later there was a general uplift of the whole region, and at the same time a reversed movement of a few hundred feet along the Ray fault, the block on the west this time subsiding, in contrast to its earlier repeated uplifts.

Summarizing the history from the point of view I wish to bring out, there was in this district an apparent lack of either igneous intrusion or important faulting from pre-Cambrian to probable Cretaceous time; at the last-named period came the granite porphyry and allied minor intrusions; and this was followed by surface volcanics (fed by dikes from below) at intervals in the Tertiary. Heavy faulting followed close upon the granite porphyry intrusion and continued to the present, and therefore the general period of igneous activity and faulting coincided and the two were evidently connected as to origin; the main mineralized area had an upward movement or growth of at least three thousand feet, which growth occurred in two distinct and separate waves, and finally, in recent times, subsided a few hundred feet.[26] I must ascribe this uplift of the fault blocks in question to the upward pressure of the igneous

[26] I will not burden these pages with an account of the reliable criteria by which this history of fault movement was deciphered. The relative effect of the recurrent fault movements, on the successive Tertiary and Pleistocene accumulations, of course furnishes the key. The problem is somewhat like that of the faulting of the Esperanza vein (Fig. 65, p. 339), but the revealed history of the Ray fault is more complex.

magma body which we know (from its extrusions) existed below; and its occurrence in two distinct and separate waves indicates periods of accumulated pressure, which became strong enough to overcome the weight of the overlying rocks. It may be that each of these uplifts resulted in some volcanic discharge near this district, though not detected in it; and that therefore there was no further upheaval till the telluric pressure had again accumulated. Similarly, the very recent subsidence may be due to magma migration from below this block elsewhere, or to a discharge of the accumulating pressure in some near-by place, so that the weight of the block overcame the residual pressure exerted beneath. Therefore, recurrent periods of uplift of fault blocks, at Ray, or in the Sierra Nevada, or elsewhere, are not regular.

The fact of the achieval of uplift in recurrent waves, however, does, it seems to me, point to the accumulation of telluric pressure in an underlying magma, up to the lifting or intruding point, and if this condition is as true of the Sierra Nevada (which is a continental unit) as it is of the Ray fault block, may it not be true of the Rocky Mountain uplift, and indeed of the whole Rocky Mountain plateau and mountain belt from Mexico to Canada, which has experienced recurrent uplifts?

The main magma which has uplifted the Sierra Nevada is an intermediate one, a granodiorite or monzonite; essentially it is the same as the average magma intruded, at the same post-Cretaceous period and since then, into the Rocky Mountain belt, from Mexico to Canada. Outliers and upshoots of similar intermediate magma occur abundantly in the space between the Sierra Nevada and the Rockies, and there seems little doubt that essentially one magma basin underlay at the close of the Cretaceous this whole western part of North America, from the Rocky Mountains west, and still so underlies. Not only is the main original magma of similar composition throughout this region, but over a large part of it certainly the same processes of differentia-

tion have gone on at about the same time (further indicating a common magma sea), as is shown by the simultaneous appearance of derived lavas of similar composition, at many different points over this whole region.

After a study of the lavas of the "Great Basin" in 1900,[27] I wrote that this whole region "southward into the Mojave desert, together with a portion at least of the Sierra Nevada, constitutes a petrographic province; that is to say, it is underlain by a single body of molten magma, which has supplied, at different periods, lavas of similar composition to all the different parts of the overlying surface. The limits of this subcrustal basin, however, are not yet defined in any direction." The general sequence of lavas, roughly outlined, was concluded to be as follows: 1, Rhyolite; 2, andesite; 3, rhyolite with occasional basalt; 4, andesite; 5, basalt and occasional rhyolite. It was postulated that there were represented two complete cycles of differentiation from an intermediate magma (andesitic or dioritic) to basic and siliceous extremes (basalts and rhyolites), as shown (a) in 2 and 3 above, and (b) in 4 and 5; and that the Eocene rhyolite (No. 1 in the series above) represented in part the final stages of a still earlier cycle. Between 1 and 2, therefore, there was a revolution and beginning of a new epoch, which consisted in the arrival in the magma basin below of a fresh supply of undifferentiated intermediate magma; and a similar revolution between 3 and 4. The corresponding lavas, which thus appeared recurrently, and are similar in composition, were called recurrent lavas.

Ball, as a result of his reconnaissance mapping of over 8,000 square miles in Nevada and California, in 1905[28] wrote: "As to the genetic relation of the magmas, the writer is wholly in accord with the view of Spurr, in the article just cited. He believes that the Tertiary lavas of the Great Basin are the representatives of two complete cycles of the differentiation of a magma of medium composition into

[27] *Jour. Geol.*, Vol. VIII, p. 638.

[28] Bulletin 308, U. S. Geol. Surv., pp. 27, 34.

acidic and basic lavas and that probably the end of a still earlier cycle is also represented." His succession is in general the same: 1, Rhyolite; 2, siliceous andesite; 3, rhyolite with occasional basalt; 4, andesite; 5, rhyolite, followed by basalt. Ransome in 1909[29] described a roughly similar succession in the mineral district of Goldfield, which I may summarize, in my own way, as follows: 1, Rhyolite; 2, latite (intermediate between andesite and trachyte); 3, rhyolite; 4, andesite and dacite (quartz andesite); 5, rhyolite, followed by basalt; 6, rhyolite, followed by basalt.

As to the age of these successive lava periods, my conclusion for this petrographic province in general, in 1900, was as follows: 1, Rhyolite (Eocene); 2, andesite (Miocene); 3, rhyolite, with occasional basalt (late Miocene early Pliocene); 4, andesite (late Pliocene); 5, basalt and occasional rhyolite (Pleistocene).

In Tonopah, it has been difficult to work out the rock sequences. As at present ascertained,[30] they are as follows: 1, Trachyte; 2, andesite; 3, rhyolite; 4, andesite; 5, rhyolite and occasional basalt.

However, No. 5 (rhyolite and occasional basalt) occurs both before, during, and after the deposition of the Siebert lake-beds; which corresponds lithologically with the Pah-Ute lake deposits of King, referred by him to the Miocene.[31] At Goldfield the same relation exists. Therefore the No. 5 rhyolite of Tonopah and Goldfield corresponds with the No. 3 rhyolite of my 1900 sequence. The basalt of this period is of an epoch distinctly earlier than the Pleistocene basalts of the Sierra Nevada back-trough, with their occasionally associated rhyolites (No. 5 of my 1900 sequence); similarly, the late Pliocene early Pleistocene andesitic cones of the Sierra Nevada (No. 4 of my 1900 sequence) belong to a distinctly later epoch than the andesite No. 4 of the Tonopah sequence. In other words, this 4 and 5 of my

[29] *Professional Paper* 66, U. S. Geol. Surv., p. 90.

[30] *Econ. Geol.*, Vol. X, No. 8, pp. 713-769.

[31] U. S. Geol. Expl. 40th Parallel, Vol. I, p. 454.

1900 sequence is not represented at Tonopah, though well shown not far west; and therefore, an additional andesite-rhyolite-basalt cycle is suggested for the Tonopah-Goldfield region at least.[32] The amended complete sequence for the region would therefore be about as follows: 1, Rhyolite[33] (Eocene); 2, andesite (late Eocene?); 3, rhyolite with occasional basalt (late Eocene early Miocene?); 4, andesite (early Miocene); 5, rhyolite and occasional basalt (late Miocene early Pliocene); 6, andesite (late Pliocene); 7, basalt and occasional rhyolite (Pleistocene).

The Pleistocene basalt and rhyolite are represented in the Goldfield section (No. 6 of my summary of the Goldfield section above).

The recurrent fresh supplies of the undifferentiated intermediate magmas recall the recurrent main periods of uplifts of the Sierra Nevada, which we have just been discussing, and which appear to be of about the same order of frequency. And, indeed, the revolution from 5 to 6 (above) and the extrusion afresh of andesites in the Sierra Nevada and throughout the Great Basin, was contemporaneous in general with the great elevation of the range at the close of the Pliocene. The earlier uplifts, their relative importance, and their exact relation to the volcanic activity is obscured in the fading geologic record of the past. The first indicated revolution (between 1 and 2) I have provisionally placed in the latter part of the Eocene. King considered that an uplift of the Sierra took place either within

[32] Direct evidence of origin by magmatic differentiation (so hard to obtain in lavas, on account of their individuality, and often so plain in intrusive rocks, especially those deeper ones which have been within the zone of differentiation and show the process of differentiation, arrested at various stages) is afforded by one of the No. 5 rhyolites at Tonopah, which shows numerous aggregates of quartz, orthoclase, and biotite pseudomorphous after hornblende, the alteration being magmatic; thus a chemical change in the magma since the early crystallization is shown, for the present rock is very siliceous, contains no hornblende, and very little biotite (*Professional Paper* 42, U. S. Geol. Surv., p. 63).

[33] Trachyte at Tonopah.

the Eocene or at the close of the Eocene, which was followed by the formation of the Tertiary lakes. As to the intervening period (marked, according to my plan, by another revolution and the beginning of a new cycle of differentiation at a period which I have provisionally called early Miocene), I have no data tending to correlate it with a known period of uplift.

Therefore, in the Sierra Nevada the recurrent main periods of uplift may have been due to the arrival at the base of the range of fresh supplies of intermediate magma, which thus passed from some deeper source where differentiation is impossible to a higher position where it could begin. In an earlier paper[34] I stated my belief that rock magmas do not begin to differentiate till they are subjected to unusual conditions; and that these conditions are supplied where magmas have moved upward to the lower portion of the zone of crystallization. Once transferred to the zone of differentiation, the magma seems capable of differentiation within a relatively brief geologic period, as shown by the Great Basin cycles, the first consummated probably during the early Eocene; the second in the late Eocene, the third in the Miocene and early Pliocene, and the fourth since the late Pliocene. It is interesting to note that the Katmai volcano of the Aleutian chain, which in Pleistocene time erupted a basic andesite (No. 6 of the Great Basin series) and which has recently broken out afresh, has now put forth a siliceous rhyolite. Such a change cannot be explained by supposing a differentiation by gravity into a heavier or more basic magma layer below and a lighter or more siliceous magma above, because then the order of eruption would be the reverse of what it is; it must be due to an active differentiation process from an intermediate magma.

My conclusions as to the sequence of lavas in the Great Basin and Sierra Nevada were found applicable by Ordo-

[34] "A Theory of Ore Deposition," *Econ. Geol.*, Vol. II, No. 8, Dec., 1907, p. 784.

ñez[35] in Mexico. In 1902[36] I further dwelt upon the fact that basic andesites (largely pyroxene andesites and frequently hypersthene andesites) belonging to the late Pliocene early Pleistocene group (No. 6) above mentioned, continue northward through Alaska (running the whole length of the Aleutian Islands); and southward through Mexico, Central America, and the Andes of South America. "It appears, then, that the whole extreme western part of the Western Hemisphere . . . is a zone occupied by what (at some periods at least) is and has been a single petrographic province." Further I pointed out that on the Asiatic side of the Pacific a line of similar late Tertiary-Pleistocene volcanoes, which have yielded characteristically andesite—largely pyroxene andesite and frequently hypersthene andesite—follow from the Aleutian Islands through the Kurile Islands, the islands of Japan, and the Philippines into the East Indies. In 1905, I pointed out[37] reasons for believing that the belt of very late Pliocene-Pleistocene andesitic eruptions continues even further than above sketched; in fact, may form a ring around the whole Pacific Ocean, indicating a single major petrographic province for this period, extending around the whole zone.

Going back to the Sierra Nevada uplift as a familiar type example: if it is true that the recurrent main uplifts have been due to fresh supplies of magma at the roots of the range, as the previous supply became exhausted through eruption, where did these fresh supplies come from? From a deeper zone surely, since that zone was beneath the zone of differentiation; and surely from a lateral direction, since the accompanying uplift of the range implies an accumulation of pressure and doubtless of material from one side or the other, or both. Considering now that this ring of uplift and igneous action extends around the Pacific, it becomes clear that the main source of the granodioritic magma was

[35] *Boletin del Instituto Geologico de Mexico,* No. 14, p. 65.
[36] *Trans.* A. I. M. E., Vol. XXXIII, pp. 332-333.
[37] *Professional Paper* 42, U. S. Geol. Surv., p. 280.

from beneath that ocean;[38] and it is a reasonable hypothesis that the whole Pacific is underlain, at a depth below the crust too great for differentiation, by magma of intermediate composition, which flows laterally slowly toward and beneath the continents and upholds their crust; and thus allows them, in spite of constant erosion, to maintain their average relatively elevated position by means of repeated uplifts. In speaking of this magma, I do not postulate a liquid—the relative rigidity will be conditioned by the pressure; and the flow is evidently very slow—as slow perhaps as the upward flow of schist, when it is pressed up by a great intrusive magma body, and as the accompanying local surface uplift.

The recurrent uplifts of the Sierra Nevada, with intervening periods of rest and erosion, correspond with simultaneous uplifts throughout most of the Cordilleran region of North America. The uplift at the close of the Cretaceous extended over this whole region; and the great uplift of the Sierra Nevada at the close of the Pliocene (as above noted), which led to the cutting of sharp canyons and the development of the present rugged topography, was apparently contemporaneous with a similar uplift elsewhere in this region, as in the Colorado Rockies[39] and the Colorado Plateau.

Thus these periods of uplift of the Sierra correspond in general nature with recurrent (but not rhythmic) continental uplifts. Geological studies show that such uplifts have occurred since the beginning of the geologic record, and that some of the major ones have affected more than one continent; they have been revolutionary, as regards continents and oceans, and the development of life. The occurrence over the world of red sandstones in the Triassic (for example) indicates at that period high continents and

[38] This chapter was written in 1918. See Bailey Willis: *Bulletin Geol. Soc. Am.*, June, 1920, pp. 247-302. Professor Willis suggests that "the igneous material which is erupted in the margins of the continents around the ocean basins comes from beneath the latter."

[39] *Professional Paper* 63, U. S. Geol. Surv., p. 32.

rapid erosion. Usually, however, there is no such marked synchrony, the uplifts being diverse and localized to a greater or less degree, not only as regards the world, but as regards each continent and each section of continent.

As to the cause of the lateral flow from beneath the oceans to beneath the continents, I see none except differences in density between these portions of the earth, which, for all we know, are original. The fact of this difference has been determined by the measurement of physicists, those of Hecker for both the Atlantic and Pacific basins indicating that the density of the different portions of these basins increases in general in proportion to the depth of the sea, or to the shortening of the earth's radius; and those of Hayford for the United States showing similarly a general decrease of density in the higher portions of the continent, with increase of the earth's radius. This supports Dutton's theory of "isostasy," or tendency of gravity to produce equilibrium of weight throughout the whole earth.[40] Applying the principle of isostasy to this discussion, subcrustal flow would be established from the originally denser portions of the earth to the originally less dense portions, and that flow would not take place in the deep portions of the earth, which would be held more and more firmly by gravity in depth, but would take place as near the crust as possible—not in the superficial crust, which cooling and release of pressure has made rigid, but in a belt just beneath this crust. This flow would uplift the crust above the less dense areas, supplying height and increased volume to offset less density; and the suboceanic areas whence the flow came would deepen correspondingly. Thus equilibrium would tend to be restored.

As erosion wore down the continents, a certain unbalancing of the equilibrium would develop, which may eventually be restored by further transfers and shiftings of subcrustal material. The history of uplifts of the Sierra Nevada, of the Rocky Mountains, and of the continents in

[40] *Bulletin Phil. Soc. Washington,* Vol. XI, 1889.

general shows that this adjustment is not free and continuous, but suggests that unbalancing by erosion is permitted to go on for long periods, during which the strains accumulate, and the impulse of the subcrustal layer to move from beneath the oceans to beneath the continents must increase, till it is sufficient to force the renewal of flowage; it then proceeds to make up for lost time, and a revolutionary period of uplift, of intrusion and volcanic action, and of folding and faulting, ensues, like that at the close of the Cretaceous, in the Cordilleran region of North America. Such a wave of transfer may have a momentum sufficient to pass the point of equilibrium; hence a backward ebb may set in, signalized by a subsidence of land; and so on like the swings of a pendulum, through alternate slight elevations and subsidences, till equilibrium be restored. Were the whole crust beneath the sea, this adjustment flowage could not take place, since there would be no transfer of material by erosion, which must be compensated; nevertheless, the volcanic islands of the mid-Pacific show that, apart from isostasy, the earth is disengaging some of its gaseous elements, which must periodically make their escape to the atmosphere where their pressure accumulates sufficiently. This consideration leads to the assumption of an additional and telluric pressure afforded by those prisoned gaseous elements which have worked up to the base of the crust, and are seeking their easiest outlet, which, while it may be found in part in volcanic suboceanic outbursts along lines of fissure, will more often be in the direction of the continents; and it is probably these gaseous elements which give the flow the momentum which tends to cause overbalancing of equilibrium, upon which follow compensating partial subsidence, and further oscillations; so that exact equilibrium perhaps is never attained.

The creep of the subcrustal magma from the ocean to the continents, or the accumulated strain which induces this creep, or both, produces a thrust from the oceans toward the continents, with consequent folding and faulting of the

continental surface, especially on the margins of the continents; this is especially noticeable, of course, in the sedimentary rocks. The shortening of the horizontal area occupied by these rocks is compensated by extension of their vertical area, producing, together with the increment of magma at the base of the crust, that uplift which tends to restore equilibrium.

Therefore, in the broadest sense, I refer practically all continental crustal movements, including folding and faulting, as well as uplifting, to magma migration or igneous intrusion. The folding and faulting of the Appalachian strata, for example, I visualize as having been due to subcrustal flowage from beneath the Atlantic. Whether this subcrustal magma gets near enough to the surface to be later exposed by erosion, and so detected, is a matter of regional or local conditions: certainly all observation, as well as all theory, shows that most of it does not.

The continents are those portions of the crust which are above sea level, as contrasted with the subocean areas; but the differences in altitude of the land areas and in depth of the oceanic areas are great and various, indicating probably great relative original differences of density in both areas. This is perhaps shown by certain relatively depressed or elevated suboceanic areas remote from land; and on the continents by certain areas which have had a constant tendency to uplift during geologic history, and certain others which have remained undisturbed, or have had a constant tendency to subside.[41]

On the continental surface, however, and near the continents (within their radius of influence) there are evidently other factors than original high specific gravity or the increase of volume by addition of volcanic rocks or igneous intrusions which have effected relative subsidence of depressed areas, just as there are other factors than original

[41] This has been pointed out by Willis (Geol. Soc. Am., Vol. XVIII, pp. 389-412), who calls the continental areas which tend to uplift positive elements, and those which tend to subsidence, negative elements.

relatively minor specific gravity or the stripping off of rocks by erosion which have raised areas of uplift. A simple "isostatic" balance does not exist, as has been often pointed out. To demonstrate the truth of this generalization, we have only to consider the oscillating up-and-down movements registered on all shore lines; and the case of the Ray fault block (p. 224), which after an elevation of several thousand feet, subsided a few hundred feet, may serve as a small-scale illustration.

Let us consider, for example, the effect of volcanic eruption and igneous intrusion. The initial stages are the gathering of the magma beneath an area of least pressure. Such an area should ideally be one of relatively less mass than surrounding regions, and may, therefore, be one of the positive continental elements, which by erosion has had its mass so reduced as to throw it anew out of balance. With the accumulation of magma beneath it, this area will ideally tend to rise, and so continue till the igneous intrusion or volcanic outburst. This (especially the volcanic outburst) lessens the telluric pressure by the escape of gaseous magmatic elements upward and eventually into the atmosphere; the upward-propelled magma masses, whether intrusive or extrusive, cool and solidify, and so contract, with the result that without much loss of weight there is a loss of volume. These two changes, as well as another cause which I shall discuss presently, call for adjustment by sagging or subsidence of the surface.

At Tonopah there has been a striking local subsidence around certain dacitic rhyolite volcanic necks (Fig. 66), which subsidence has been accomplished by faulting which does not affect the necks[42]; showing that not only the necks have sunk during or since consolidation, but that they have dragged down the surrounding rocks as well. Contrast this sag after intrusion with the punching up from below of a solidified rhyolite volcanic plug ("spine") at Mount Pelée

[42] *Professional Paper* 42, U. S. Geol. Surv., p. 47; Plates VII and VIII.

and at Katmai,[43] indicating telluric magma pressure at the time of eruption; at Tonopah, also, the less bulky plugs of a more siliceous though nearly contemporaneous alaskitic rhyolite not only have not sagged, but in one case the latest recorded movement was a continued upthrust after consolidation.[44]

But at Tonopah not only was there marked subsidence immediately around dacitic rhyolite necks, but the entire mapped area in which these necks occur has subsided to a less degree. This area is over five square miles, and passes out of the area mapped in all directions, so that the total amount of the relatively sunken area is uncertain, but probably very large. On the margins of this sunken area, the subsidence amounts probably to a few hundred feet, but in half a mile from the margins appears to be upward of a thousand feet, between the volcanic necks, and close to the volcanic necks probably twice that much.[45]

These volcanic necks came up through the finely stratified beds (tuffs), which were formed in a lake of large extent, which covered a large area in Western Nevada. The beds are mainly of volcanic tuffs and ash, and were formed during a period of great volcanic activity.[46] Rhyolitic lavas not only penetrated the beds and overflowed them, as described above, but occur as interbedded flows in the lower beds, and the whole lake series is underlain by rhyolite. Therefore, the beds were formed during this general period of extensive rhyolite eruption (No. 5 in my sequence), but at the close of the most active period. It was and is my hypothesis that this lake basin was due to subsidence of the crust, brought about by the loss of volume consequent upon the volcanic outbursts. In view of the subsidence at Tonopah, described above, and actually demonstrated to be due to this cause, it is evidently a competent one for the forma-

[43] *Ohio Jour. Sci.*, Vol. XIX, No. 2, p. 114.
[44] *Professional Paper* 42, U. S. Geol. Surv., p. 50.
[45] *Op. cit.*, pp. 53, 140, 200.
[46] *Op. cit.*, p. 52.

tion of a large and deep lake basin in the area of greatest volcanic outbreak.[47]

Of such origin (subsidence after volcanic eruption) is probably the basin of Lake Mono, in California. The valley of Mexico, in which Mexico City is situated, is very likely an area of subsidence following volcanic outbreak.

I think we are warranted in extending this explanation, as an hypothesis, to account for all the great and uneasily shifting areas of subsidence which have formed in the Nevada Plateau region and have been occupied by lakes from the Eocene to the present, the period of this crustal subsidence and shifting being identical with that of the recurrent intense volcanic activity whose sequence has been discussed above. And as subsidences are the reverse of uplifts, and may be, so to speak, paired off with them, and since, for each type of subsidence due to a given cause there is a corresponding type of uplift, the relatively large areas of uplift in the Great Basin during the same general period may be assumed to have been due to the accumulation beneath of magma under telluric pressure and charged with gaseous elements. When it comes to more detailed areas,

[47] Sir Archibald Geikie notes that the volcanic region in the north of Ireland "was evidently the site of a lake during the volcanic period. . . . It may here be remarked that the tendency to subsidence . . . seems to have characterized this region since an early part of the volcanic period. . . . But long after the eruptions ceased, a renewed sinking of the ground gave rise to a sheet of water which now forms Loch Neagh. . . . We may conceive that after the cessation of the outflows of basalt the territory overlying the lava reservoir that had been emptied would tend to subside." . . . And

"There seems to have been commonly a contraction subsidence of the material in the vents, with a consequent dragging down or sagging of the rocks immediately outside, which are thus made to plunge steeply toward the necks." ("Ancient Volcanoes of Great Britain," Vol. II, pp. 205, 450.)

Willis (*Bull. Geol. Soc. Am.,* Vol. XVIII, p. 409, etc.) remarks that in the Lake Superior region volcanic and plutonic activity existed on a very large scale until the close of the Keweenawan, when it ceased, apparently forever. During the igneous activity the region subsided, but since then has had a constant rising tendency. Although Willis did not offer the explanation of this fact which I am now suggesting, it seems to me a very likely one.

I have sought to demonstrate (early in this chapter) that local domical uplifts, sometimes very abrupt, are due to this same cause; and (to repeat) that around volcanic necks, as at Tonopah, abrupt local subsidences may be due to the diminution of pressure and volume of a local magma protrusion or plug. I wish now to discuss certain observations I have made in divers parts of that belt which lies parallel to and east of the Sierra Nevada, which I have earlier in this chapter called the Sierra back-trough belt, and described as showing the effect of recent deformation, with uplift of ranges and depression of valleys, and with the formation, by flexing or faulting or both, of domes or fault blocks as ridges, and of basins or valleys. A marked contrast of mountain and valley, abrupt transitional slopes, and great differences in elevation within a short distance characterize this region.

Let me instance the Walker River range, in Nevada, which lies about fifty miles southeast of Carson and near the eastern border of this recently deformed belt. This range has a length of fifty or sixty miles, and a width (between desert valleys) of five or six. In contrast to the typical desert ranges of the Nevada Plateau to the east of here, but like the Sierra Nevada to the west, and the intervening Pine Nut and Sweetwater ranges,[48] this range is decidedly asymmetric, having a comparatively gentle slope on the west and a bold straight scarp on the east. Granitic rocks (post-Jurassic, like those of the east face of the Sierra Nevada) form the steep eastern face of the Walker River range, while overlying Tertiary volcanics form the longer western slope.[49] Late Tertiary gravels also occur far up on the western slopes, overlying the volcanic flows. On the east of the Walker River range is Walker Lake, about one-third the length of the range and nearly as wide: parallel to it and lying immediately at its base. This is an inclosed basin, without outlet.

[48] Bulletin 208, U. S. Geol. Surv., pp. 120, 125.
[49] *Op. cit.*, p. 115.

During the many occasions that I have traversed or skirted this range, I have observed it from the point of view of its origin. The range was assumed by Russell,[50] to be due to uplift along a fault at its eastern base, and I have recognized the value of this hypothesis: nevertheless, I have always been impressed with the evident relation of Walker Lake to the fresh eastern scarp, which shows only recent erosion, and I have entertained the alternative hypothesis that this bold scarp was in part at least due to lake erosion. The effect of lake erosion on the east face of the Walker River range is proved by high and deep terraces in the northern portion, one or two miles in width, and composed of great angular and subangular boulders derived from the mountains above.[51]

In my later observations, however, I have been impressed with the fact that apparently the deepest side of the lake is the west side, along the base of the range; that the lake lies opposite the central part of the range, that both its east and west shores are parallel to the range, and its width is not far less than that of the range. Moreover, the highest point in the range (Mount Grant—elevation 11,303 feet) lies opposite the south end of the lake, (elevation 4,083 feet), from whose waters it rises as a steep scarp. The contrast is, to be sure, not accurate, for the highest broad stretch of the range (comprising elevations above 10,000 feet, and including Mount Grant at its northern end) is situated to the south of the lake basin.

The fact that the deepest side of the lake lies under the steep east scarp of the range, however, shows that the conjunction between scarp and lake cannot be due to the erosion by the latter of the base of the former; for in that case the lake at this end would have been filled up with debris, driving the water away from the scarp. A comparatively recent deepening of the lake on the west side, more rapid than erosion, seems clearly indicated; and such a recent

[50] *Monograph* XI, U. S. Geol. Surv.

[51] Bulletin 208, U. S. Geol. Surv., p. 117.

crustal movement along the line at the base of the range lends strength to Russell's hypothesis that the range is due to Pleistocene uplift along a fault at its eastern base, and is essentially a monoclinal fault block, like the Sierra Nevada. However, this explanation is not wholly satisfying. A north-south basin rising to the north and south, lying at the foot of a north-south range of limited extent which falls away to the north and south, suggests a certain connection, pairing, or compensation between ridge and valley.

Turning now to the most picturesque part of this Sierra Nevada back-trough, that near Death Valley: is it a coincidence only, I have asked myself, that the highest and the lowest points of the United States should be only eighty miles apart? Mount Whitney, in the Sierras (elevation 14,501 feet) is that distance from the bottom of Death Valley, 274 feet below sea level, a difference of elevation of 14,775 feet. This is a region of great differences of elevation between ridges and adjacent valleys. Telescope Peak, in the Panamint range (which range bounds Death Valley on the west), is 11,045 feet high, and is twelve miles southwest of the deepest part of the valley; at the west base of the Panamints, and fifteen miles southwest of Telescope Peak, the valley at Ballarat has an elevation of only 1,067 feet. We have, fortunately, careful topographic mapping for this section by the United States Geological Survey.

Viewing Death Valley as due in part at least to recent crustal disturbance (as we must), we note from the topographic maps that the main line of the most recent dislocation (by flexing and accompanying faulting) is indicated to have been on the east side, at the base of the Funeral range, for here there has not been time for erosion to form debris slopes (wash aprons) at the foot of the scarp. Owens River Valley, which lies east of the Sierra Nevada, has an elevation of between 3,500 and 4,000 feet; the Panamint Valley, next east, about 1,000 feet, as stated; then comes Death Valley, below sea level. Thus the successive valleys in this section, from the Sierra Nevada east, grow deeper to

Death Valley; but on the east side of Death Valley the dislocation above alluded to separates this recently deformed belt on the west (which I have called previously in this discussion the Sierra Nevada back-trough belt) from the Nevada Plateau and its older mountains of predominant erosion on the east.

Is it a coincidence that Owens River Valley lies parallel with the Sierra Nevada and under its east-facing scarp; that the descent of this valley to the south is attended by an increase of height of the bordering Sierra; and that the lowest part of the drainage, where it is gathered in Owens Lake, is only fifteen miles southeast of the top of the highest peak in the range—Mount Whitney? All this suggests a principle of compensation.

This principle, tentatively stated, is that in this belt high mountains of recent uplift are paired to a certain extent with corresponding adjacent although relatively minor depressions: as, Walker River range with Walker Lake; the top of the Sierras with Owens Lake; the Panamint range with Death Valley; and in general the relatively (although irregularly) depressed belt lying between the Sierra Nevada and the Nevada Plateau, which has been occupied by large lakes in the Tertiary, and by their remnants and sunken dry basins at present, with the whole great mass of the Sierra Nevada.

If there is any solid foundation underlying this my suggestion of a principle of compensation, I see two alternative explanations which appear to me worthy of mention. First, if a range of uplift (let us say the Sierra Nevada, for example) owes its recent uplift to the accumulation of magma beneath it, the drainage of magma underlying immediately adjacent belts may cause relative subsidence. As for myself, I have rejected this explanation because such an accumulation of magma at the roots of uplifts should be drawn from a wide area, and not a narrow belt: belts adjacent to the uplift would tend to rise also, although not in the same proportion.

The second explanation, on which I look with favor, is that the weight of very high recent uplifts may be so great as to cause them to sink back, carrying down as parallel depressions the adjacent strips, and that the depressed Sierra back-trough belt is due to the sagging of the Sierras; that as the range was repeatedly uplifted since the Cretaceous, the back-trough was repeatedly deepened, and that the depression which was recently formed, and is still going on, is consequent upon recent uplifts of the range, still spasmodically occurring. Since the Sierra is not a range due to folding, but a fault block, the back-trough depression cannot be explained as a major fold or geosyncline, which, moreover, its structure shows it is not; nor, as above pointed out, does any acceptable theory of fault blocks account for the pairing of uplift and depression which seems to exist elsewhere. The Sierra Nevada back-trough is the most satisfactory example, although the detail of the Walker River range suggests a nicer balancing.

It is easy to suspect other examples of detailed "pairing" in this belt; for example, the Inyo or White Mountain range adjoining and just north of Owens Lake contains at this point several peaks varying from 10,600 to 11,100 feet in height, and might be thought to be paired with Saline Valley, 1,100 feet in elevation, lying immediately under its precipitous northeastern face; similarly, I have thought that the dry-lake basin of Clayton Valley, which lies at the eastern face of the most massive part of the Silver Peak range, may be "paired" with it in this sense. There are, however, as I have above noted, various causes contributing to the deformation of these valleys, and each should be studied with the utmost care. Subsidence after volcanic eruption, the blocking of valleys by recent lava flows, and the effects of broad warping, affecting mountain and valley alike, are among these, as well as this other cause of gravity adjustment in sympathy with the sagging of heavy ranges, which I think I have detected, and which I believe to be a factor to be reckoned with.

The definition and explanation of the Sierra Nevada back-trough leads to the consideration of a feature of the world's crustal relief which has engaged the attention of geographers and geologists. Around the margins of the Pacific, soundings show in many places deep and narrow troughs bordering the continents or the margin of the submerged continental shelves. This phenomenon is rare in the Atlantic. In the Pacific such a trough lies along the west coast of South America, opposite portions of Peru and Chile, between Callao and Valparaiso; it is found at intervals close to the southern margin of the Aleutian Islands, and just east of the Islands of Japan and of the Philippines; a similar deep trough borders the eastern margin of the submerged Australian plateau, and another the southwest coast of

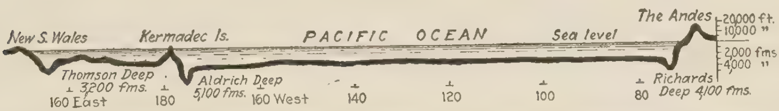


FIG. 51.—Section across the Pacific Ocean, from South America to Australia. After James Geikie, "Mountains, Their Origin and Structure." On the right, the Andes Mountains, and their paired foredeeps, are shown.

Australia. (Fig. 51.) Suess called these "foredeeps." Believing that the folding of rocks, the elevation of ranges, and the growth of continents was due to crustal shortening resulting from cooling and contraction, and the collapse of the ocean basins (like the wrinkling of the skin of a drying apple), he concluded that against primitive cores of continents successive ridges of folding were formed (by the resistance of these cores to the lateral pressure of the collapsing crust), producing successive mountain ranges, which advance toward the oceans, and so enlarge the continents. The foredeeps he considered as characteristic of the belt lying immediately between the last line of uplift and the main oceanic basin.

He interpreted the Asiatic foredeeps as due to the subsidence of an area of the crust affecting all the region in the direction of Asia; and believed that across this sunken area

the successive ranges advanced, and that in some cases where there are no foredeeps it may be because the advancing ranges have obliterated the primary area of subsidence.

As to the cause of this assumed primary subsidence, no explanation is given. James Geikie[52] has rejected Suess' explanation, offering a number of valid objections; and as an explanation of these marginal troughs he has argued that the formation of the mountain chains on the margin of the Pacific, "would necessarily relieve the crust within the oceanic basin, and thus facilitate the sinking of the sea floor." He points out that many of the uplifts which girdle the Pacific are post-Tertiary, and that the corresponding subsidence of the ocean floor would produce tension, at the margins of the continents or continental plateaus, or at the outer margin of the latest ranges, which would cause post-Tertiary sharp flexing or faulting. Some of the troughs, he believes, may be due to step faults, while some may be geosynclines.

Geikie's explanation does not satisfy me; it does not explain the troughs. On his hypothesis the steep transition from mountains to sea floor without marginal troughs might be explained, as along the California coast; but not the narrow crustal troughs along the South American coast, whose depths reach over a thousand fathoms (6,000 feet) below the deep (about 3,000 fathoms—18,000 feet) ocean floor on the west. And the explanation I wish to offer for this South American instance is one which Geikie mentioned with some favor, but nevertheless rejected;[53] and is the same as I have offered above for the minor California phenomena which I have just described.

The belt of coastal troughs between Callao and Valparaiso is certainly "paired" with the highest portion of the Andes, which has numerous peaks averaging 20,000 feet above the sea. (Fig. 51.) Opposite Valparaiso, Mount Aconcoqua is nearly 23,000 feet high, and Mount Illampu, opposite the

[52] "Mountains," 1913, p. 222.
[53] *Op. cit.*, p. 226.

central point in the chain of troughs, is 21,500 feet. The Andes which border this coastal depression form a belt, not only of Tertiary, but of recent, severe volcanism and uplift; and the width of the coastal trough is very much less than that of the mountain ranges. The only explanation which, it seems to me, satisfies the conditions, is that the foundations of the Andes here have sagged and are sagging under the weight of the great and rapid volcanic accumulations and uplifted rocks, and are dragging down with them the adjacent ocean floor.

These examples from the west coast of North and South America show that along this belt of Tertiary, Quaternary, and actual volcanic upheaval and outburst, the crust is not in static equilibrium, but is in a condition of unstable equilibrium, which seeks adjustment, but is prevented from attaining it by fresh accessions of magma at the roots of the ranges, which at times is intruded and even poured out at the surface; these magma increments cause the ranges to be uplifted and the crust overweighted anew. Telluric pressure in the magma, the pressure for escape of accumulated volatile earth constituents, disengaged from the earth's interior, and the momentum of accumulation and extrusion resulting therefrom, are probably responsible for the repeated violent accessions of magma along lines of weakness and the consequent disturbances of equilibrium.

The theory of "isostasy" was proposed by Dutton. He defined it as follows: "For this condition of equilibrium of figure, to which gravitation tends to reduce a planetary body, irrespective of whether it be homogeneous or not, I propose the name 'isostasy'."

Instrumental observations, above referred to (p. 234), show that the United States and adjacent areas, as well as the Atlantic and Pacific basins, are approximately in equilibrium or isostasy, but that the large mountain ranges are probably not in isostatic equilibrium. It is a corollary of my above-stated conclusions, that this isostasy is, indeed, only true in a general way, and that locally inequilibrium

exists, to varying degrees. Indeed, I do not believe that the crust is ever really in equilibrium, as the continual uplifts, depressions, and warpings of the crust, evidenced by changes of shore lines and disturbance of drainage, testify. It is constantly seeking equilibrium, and having it constantly disturbed anew by dynamic earth forces.[54]

Some further discussion of the marginal troughs of the Pacific is necessary. Inspection of a map of these Pacific depressions shows: First, that they do not always occur, even along bold mountainous coasts. For example, there are none along the northwest-trending Pacific coast of North America, but they do occur along the south margin of the Aleutian Islands, where the land mass is much less. Second, that these marginal troughs front in some regions, not the coast of the continent, but the outer margin of the partially deeply submerged continental plateau. This is true of the Aleutian Islands troughs, and of those bordering the Japanese Islands (the bottom 4,600 fathoms, or 27,600 feet below sea level). Therefore the depressed areas cannot be paired solely with the mountainous islands which they border; they must be due to the recent general sagging, not only of these islands, but of the continental shelf and the continents back of these islands. The marginal trough which follows the southwestern coast of Australia, at a little distance from shore, cannot represent a sinking due solely to any special mountainous masses, but must represent the sinking of at least the southwestern part of the Australian continent as a whole. Therefore, the relative local compensation suggested between the high Andes and the adjacent troughs is only a local manifestation of a larger similar condition: it is the weight of the high Andes *plus* the weight of the whole west side of the continent which has

[54] It is easy, from a study of maps of the world, to pick out certain features which may be marginal troughs consequent upon the sagging of great mountain masses; for example, the Ganges Valley bordering the Himalayas, and the Po Valley in front of the Alps. I understand that the strata on the flanks of the central granite of the Himalayas dip *in* toward the mountains.

produced the sag. The Andes is the mighty straw which has broken the continental camel's back of South America.

The occurrence of these marginal troughs girdling the Pacific at intervals adds another feature to the distinctive characteristics which I have previously pointed out as on a grand scale bordering this ocean—namely, the most persistent of the earth's lofty mountain belts, and the belt of the earth's most active and extensive recent volcanism, showing similar Pliocene-Pleistocene lavas.[55] Around this ocean, then, the Tertiary and post-Tertiary uplift of the bordering continents, en masse or en bloc, has resulted in overweighting them, so that the continents, both land area and submerged continental shelf, are sagging. The amount of extruded lavas is not sufficient to account for this phenomenon of abnormal increase of weight, which means abnormal accretion of new material; it must also be due to accretion under the continents by lateral flowage, which can have come only from beneath the suboceanic crust.

It is clear that these marginal troughs are not only very recent, but have been formed with great rapidity; otherwise, they would have been filled with sediments from the adjacent land as fast as formed. The variable relative speed and amount of erosion and crustal deformation determine whether the actual sea bottom along this sagging belt shall be deeper, equal, or shallower than the ocean bottom further off shore. The problem is similar to that regarding the relative speed of erosion and deformation in determining land forms, such as mountains, and, like it, depends on such factors as climate, extent of watershed, and relative elevation of the land, as well as the rate of subsidence of the trough. It is likely, therefore, that there may be a coastal trough along the west coast of North America, whose sagging has been more than compensated by sedimentation.

From the fact that in past ages great thicknesses of sedimentary rocks have been deposited in slowly sinking coastal

[55] *Professional Paper* 42, U. S. Geol. Surv., p. 280.

basins such as that in which the strata now folded into the Appalachian mountains were deposited, it has been held by many geologists that the accumulating sediments produced the gradual subsidence, by their weight. On the other hand, it has been pointed out that this is an unsubstantiated theory, as the subsidence may have nothing to do with the weight of the sediments. The observations and considerations which I have pointed out above would furnish some reason for believing that the isostatic adjustment is indeed delicate enough for the formation of depressions in the way postulated, in some regions. Nevertheless, the deep unfilled coastal troughs of the Pacific margin, above discussed, are certainly not even in a minor way due to the weight of sediments accumulating in them, as Geikie has pointed out[56]; therefore those marginal troughs (geosynclines), which have been filled with sedimentary rocks as they deepen, may have been due to the sagging of an overweighted continent. Such a continent is evidently one of great relief, of high mountains and rapid erosion: a marginal trough belt would tend to sink, first on account of the continental sag and next because of the weight of sediments.

Erosion of the land mass would restore the equilibrium, but would tend to continue till the continent was underweight; and go on till accumulated strains were sufficient to initiate the landward subcrustal magma flow from under the ocean. This flow, it would seem, may acquire sufficient momentum not only to restore the lost mass and average density, but to exceed it, especially where an actual line of eruption is initiated, so that the former underweight section of the crust may become again overweight, with resultant sagging, accompanied doubtless by temporary forcing back of the subjacent magma accumulations. As a zone of outbreak becomes thus heavily weighted with piled-up lavas and accumulated underlying intrusions, the still active magma in depth will tend to seek thinner and weaker adjacent sections of the crust. Such a section, for example,

[56] "Mountains," 1913, p. 242.

would be provided by the coastal trough which lies in front of the Andes, as described; and eventually a line of volcanic outburst may be initiated along this trough, creating a new coast range of uplift and volcanic accumulation.

The gentle and patient reader must some time ago have wondered whether I had forgotten that I was writing about ore deposits. Let me hasten to assure him that I had not. The relation between magmas and ore deposition is so intimate that whatever explains one elucidates the other; the igneous and magmatic history of the Cordilleran region of North America is closely connected with the history and nature of ore deposition; and the tracing of a common magmatic general history for the post-Cretaceous period in the lands encircling the Pacific, and therefore apparently for the crust beneath the Pacific, helps us to understand the nature and extent of the ore deposits in this peri-Pacific ring. For in addition to the points above made as characteristic of this ring, I have in an earlier publication[57] stated that it also was "a belt of enormous and roughly uniform later Tertiary mineralization, involving great concentration of silver and gold"; and so defined a major peri-Pacific metallographic province, coextensive with the major petrographic province.

The distribution of similar late Tertiary ores coincides with that of similar late Tertiary igneous rocks, with which the ores are genetically connected. My own knowledge of the similarity of these late Tertiary ores includes deposits in the United States, Mexico, and Nicaragua. Available reports concerning deposits in the Andes of South America, in Japan, the East Indies, Borneo, Celebes, and New Zealand, show rich mining districts comparable in general characteristics with Tonopah and Goldfield, in Nevada, which was the starting point of my study. These ores are all associated with Tertiary siliceous and intermediate lavas (rhyolitic and andesitic lavas); carry as chief value silver and gold in widely varying proportion; contain primary

[57] *Professional Paper* 42, U. S. Geol. Surv., p. 287.

silver sulphides, and occasional tellurides and selenides. I called the province in the western United States characterized by these ores the Nevada province, to distinguish it from the California province, whose ores are associated with post-Jurassic granitic rocks. It is only the Nevada type of ores which I have traced around the Pacific.

The fascinating correspondences and sequences of magmatic history around the Pacific (including ore deposition) are probably typical of the world's history in the past; but in this peri-Pacific province are so recent as to be not only decipherable but unmistakable. Elsewhere we have to a larger extent deeper rocks, laid bare by erosion: hence the shallow-seated type of ores of the Nevada province has been stripped off, as well as the accompanying surface volcanics; and, instead, we get various types of intrusive rocks, with accompanying characteristic ore deposits, which extend our vision deeper into the crust.

CHAPTER V

The Sequence of Ore Magmas

This chapter shows that the metalliferous veins or veindikes which are the final stage of magma differentiation have an orderly temperature-pressure sequence, ranged in vertical zones above a focus of heat below, and in horizontal concentric rings around a central focus; by superposition of one metal type on another with normal falling temperature (and by superposition in the reversed order with the frequently encountered rising temperature) compound veins are formed.

IN CHAPTERS I AND II, I pointed out the origin of pegmatites as late products of differentiation from magmas; that these pegmatites are locally metalliferous, especially as regards tungsten, tin, and molybdenum; that a later stage or further differentiation produces gold-quartz veins; and further that the residual magma from the gold-quartz vein stage may precipitate massive arsenopyrite (typically auriferous), pyrite, or chalcopyrite; that, after such massive chalcopyrite, massive blende may follow as a slightly later and overlapping stage (as in the case of the Mandy), indicating the zinc-bearing solutions or magma to have the same relation to the copper magma, as this to the gold-quartz magma, as this to the pegmatite magma, and this to the granite—in short, that the blende injection was still a magmatic stage, a further step in the process of differentiation.

From this I passed, with somewhat of a gap as regards the process of differentiation (for my main theme was really the mode of injection), to massive sulphide veins (galena-blende) of the Georgetown district (Colorado); and with another gap (and for the same reason) to the silver-gold ores of Tonopah. Having discussed the manner of injection of these veins as highly concentrated solutions and in some

cases apparently pasty fluids, in Chapter III I inquired into the manner and reason for the injection, or intrusion, or surgence, of igneous rocks or pegmatites or injected mineral veins, the problem being apparently similar for all these magmatic variations. Having deduced the principle of telluric pressure resident within the magma, enabling magmas to rise forcibly and invade by their own strength (probably through the expansive forces of their gaseous constituents), in Chapter IV I followed at length the evidence of upwelling or surgence due to this property of magmas, and traced to this cause local domal uplifts, the uplifts of ranges, and the maintenance of the continents by uplifts, and finally pointed out briefly the close connection of ore deposition with these magma movements.

It will now be in order to revert to the study of the stages of ore-bearing magmas, which I left with the discussion of the intrusive chalcopyrite and blende of the Mandy, in Manitoba, and the immediately subsequent more aqueous magma which had produced large masses of pyrite (carrying some copper, galena, and blende in places) by replacement of schist. This study will be best arrived at by a review of different occurrences. In order to focus the inquiry somewhat, let us take first a certain range of variation—say the variation or relation of the pegmatite, gold, copper, arsenic, zinc ores. There is no natural break in the sequence, as will presently appear. I shall not repeat the specific evidence I have offered in the previous chapters, but will mention it briefly, add a few new observations, and pass on to the consideration of other stages.

I have described already the transition in the Yukon country of Alaska, from pegmatites to gold-quartz veins; in the Silver Peak district of Nevada, from pegmatites through gold-quartz veins to massive auriferous arsenopyrite—giving the skeletonized succession pegmatite, gold, arsenic; and at Herb Lake, in Manitoba, the succession from barren pegmatite through molybdenite-bearing pegmatite to gold-quartz veins and thence to auriferous arsenopyrite—

or, more simply, pegmatite (molybdenum), gold, arsenic; in the same region, in the Flin Flon and Mandy district, the succession (assumed: pegmatites, gold-quartz veins) massive chalcopyrite, massive blende; or (assumed: pegmatite, gold) copper, zinc. In other words, the residual from the gold-quartz veins deposits massive sulphides containing always iron, and sometimes iron alone—(pyrite); or, with copper, cupriferous pyrite or chalcopyrite; or, with arsenic, arsenopyrite. Pyrrhotite occurs in large quantities in this district at the same general stage. Later than all these is the zinc (blende). But though pyrite, pyrrhotite, arsenopyrite, and chalcopyrite are thus shown to occur at the same general stage—later than the gold-quartz veins and earlier than the blende (and galena, as it will presently be shown) veins—these various sulphides actually often occur separately, and so really represent distinct substages, concerning which we must seek additional evidence.

The regional association of copper ores with gold-quartz veins is characteristic of many districts as well as the Manitoba district mentioned. It is exhibited, for example, in California, as in Shasta County. In all these cases the chalcopyrite is seen to be dependent upon the same intrusion as the gold-quartz veins, but to be subsequent. The Appalachian region of gold-quartz veins shows the same relation. Note that, in the above-mentioned regions of plainly deep-seated veins, blende, galena, and silver are practically wanting, on a commercial scale; although normally, as will be seen, the blende and galena depositions follow the copper. The blende, galena, silver zones have hence been eroded, and, therefore, normally occur at a markedly greater elevation than the copper, gold zones—by many thousands of feet, apparently.

In all these cases which I have seen, most of the metallic sulphides in the veins have tended to be deposited later than the quartz, along fractures which sometimes are parallel to the walls of the quartz vein, sometimes only slightly oblique and sometimes markedly so, and sometimes transverse. I

have noted all these cases. Thus oreshoots are formed, short or long[1]; and, in many mines of California that I have seen, oreshoots thus determined by the intersection of subsequent sulphides constitute the only pay ore ("ribbon quartz"). Not only is the later ore deposited in the quartz, but in the adjacent wall rock, which, although soft and without quartz, is frequently a valuable ore. Where such oblique or transverse fractures diverge far from a quartz vein, however, as explained in the case of the Herb Lake veins, they tend to scatter and lose themselves, and so to yield no enrichment localized enough to become ore. These later metallic sulphides, in California and the Appalachians, were deposited with little quartz or other gangue.

As Lindgren long ago pointed out, the wall rocks of the California veins are not silicified, but are altered to carbonates, notably siderite. The fact that silicification has not affected the wall rock is evidence that the quartz veins were not formed by slow precipitation from highly heated waters. Such agents would have replaced the walls with silica. The lack of true precipitation banding in the gold-quartz veins of California also negatives this idea, and shows that the veins do not represent the gradual closing of pre-existing open fissures by progressive precipitation; and that they are not replacement veins which have permeated and replaced crushed-rock zones is shown by their sharp contact with walls which show no silicification. They are, therefore, injected or intrusive quartz veins, and the injected magma must have been a very highly concentrated silica solution. It is significant, perhaps, that in the main gold regions of California and the Appalachians, where copper ores are also frequently found, not only, as above noted, important deposits of lead, zinc, and silver are wanting, but large deposits of arsenopyrite are also not common. This may have a similar significance; namely, that the arsenopyrite, which

[1] There are also other modes of formation of oreshoots. Some of them will be discussed later. Oreshoots contemporaneous with the quartz veins are frequent (see p. 694, for example).

appeared to closely follow the gold-quartz at Herb Lake and at Silver Peak, and the relative age of which (as compared with that of chalcopyrite) was difficult to determine in the former district, is normally subsequent to the chalcopyrite, and hence, like the galena and blende, occupied a higher zone, which has been eroded. For the sequence of one phase of magmatic consolidation after another can only mean that the relatively later phase is deposited, or freezes, normally at a higher elevation or cooler zone than the earlier phase: the very fact of its remaining fluid shows that under the conditions determining the solidification or crystallization of the earlier phase (which conditions, as in the case of all igneous magmas, we must believe to be certain critical points of temperature and pressure) it still maintained its fluidity and hence its intrusive or surgent potency, to rise until its own critical temperature is reached, and by precipitation it is separated or differentiated from the still residual magma solution. The existence of a regular sequence of metallic deposition, observed in many places, moreover, indicates the fact of the original common source of these metals—due to and part of a single magma demonstration. Were they from independent sources there would be no regular sequence; indeed, they would not follow one another so closely at all, as they do.

The vertical range of ore deposition of gold-quartz veins like those of California and the Appalachians must have been very great. In California, the deepest mines are several thousand feet down—over a mile on the dip of the vein in the Kennedy, in Amador County on the Mother Lode, and there is no noticeable difference of mineralization from top to bottom. A vertical range of at least several miles is indicated.

In the Appalachians and California, the pyritic deposits are not only of chalcopyrite, but of pyrite also, as in the Manitoba region described. In the Appalachians, the large pyrite deposits, worked as a source of sulphur, appear to belong to this class. Of these I have examined only the

Chestatee, in Georgia, which contains a little copper and gold, and is of the type in question—a massive sulphide deposit, with very little gangue. This orebody is in schist. On the other side of the continent, a similar deposit which I have studied is the Dairy Farm mine, in Placer County, California. This deposit, situated in the general region of a great granodioritic intrusion which shows every evidence of differentiation, and complex progressive intrusions, with attendant stresses and shearing, is of the same massive pyrite, with a little copper and gold.

More definite data as to the relation of the copper zone to the arsenic zone—the relation of copper pyrite and arsenopyrite—are afforded by the ores of Matehuala, San Luis Potosi, Mexico, to which district I have already made reference (p. 198). It has been studied by myself and assistants and described in a paper by myself, Mr. Garrey, and Mr. Fenner.[2] This district is illustrative of the copper, arsenic, zinc, lead sequence. The phenomena are exceedingly clear and convincing, and many principles have been deduced from them with a certainty of correctness. An intrusion of monzonite necks, in limestone and shale, was followed by the deposition of lime silicates (such as pyroxene and garnet) and metallic ores. Study shows a definite and regular sequence of earthy-mineral formation: first came the formation of aluminous pyroxenes and garnets (alumina-lime silicates); next of ferrous pyroxenes and garnets (iron-lime silicates), the ferrous pyroxene changing over into a ferrous hornblende toward the last (Fig. 52); afterward quartz and fluorite; and lastly calcite. Metallic minerals were deposited at the very close of the iron-lime silicate deposition, and during the quartz-fluorite deposition.

The sequence of the metallic minerals is also established. The first were slightly cupriferous pyrites, which gradually became richer in copper so as to form a chalcopyrite ore not far inferior to that of the Mandy (p. 110). Next came on gradually the deposition of arsenopyrite, with or with-

[2] *Econ. Geol.*, Vol. VII, No. 5, p. 444, 1912.

out quartz and fluorite. This arsenopyrite, as the stages progressed, gave way to pyrite and pyrrhotite. The arsenopyrite-pyrite veins are both auriferous and argentiferous, and become important as commercial sources of silver and gold, especially in the La Paz mine. Subsequent to the arsenopyrite-pyrite period came the formation of zinc-blende; and, still later, of galena. Calcite veins, without metallic minerals, form the last stage, in rare cases there being a preliminary copious formation of celestite (strontium carbonate).

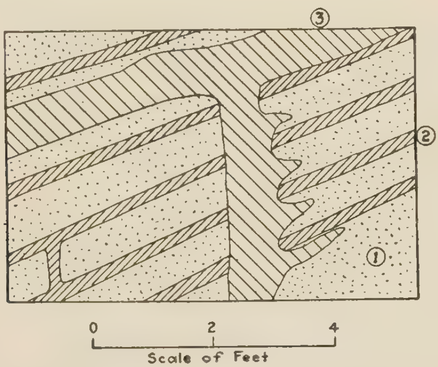


FIG. 52.—Matehuala, San Luis Potosi, Mexico. Cobriza mine, Carmen tunnel. Vertical drawing showing later age of dark silicates (which are closely associated with sulphides) and earlier age of barren red-brown silicates. 1, Dark-blue limestone; 2, red garnet bands, replacing limestone; 3, dark-green silicates, both garnet and pyroxene, with sulphides.

The gangue minerals, including the various silicates, have formed by replacement of monzonite (Fig. 53) and limestone alike. Therefore, the invading solutions, or magmas (for they were clearly the after-phenomena of the intrusion, and ascended along the fractured monzonite necks), contained all the elements which the deposits contain. The changing solutions or magmas are thus found to have been:

1. Alumina-silica-lime.
2. Silica-lime.
3. Silica-lime-iron (and other metals).
4. Lime.

If we assume that the lime may have been absorbed in passing through the limestone in the ascent, the original magmas or solutions, as differentiated products, were:

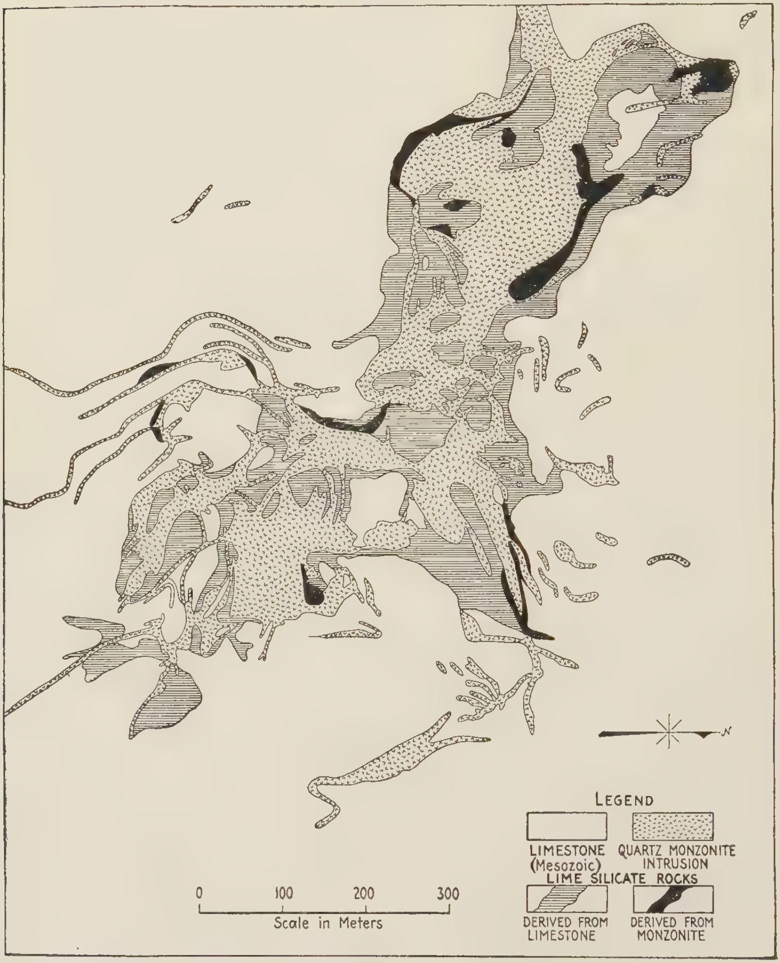


Fig. 53.—Dolores mine area, Matehuala, San Luis Potosi, Mexico. Map showing lime-silicate rocks, derived from alteration of monzonite and of limestone.

1. Alumina-silica.
2. Silica.
3. Silica-iron (and other metals).

It is pointed out in the paper referred to that (1) corresponds to alaskitic magma or solution, except for the alkalies; and (2) to the pegmatitic quartz which follows the alaskite pegmatite in the normal course of igneous differentiation. The solutions are, therefore, believed to have this origin, and the formation of lime silicates instead of quartz and feldspar is believed to be due to the lime derived from the limestone. The gold-quartz vein epoch of ore deposition is here represented obscurely, if at all, by auriferous wollastonite (lime silicate); but the copper ores are of the same type as those (like the Mandy, p. 110) which follow the gold-quartz vein stage in regions where there is no limestone. Our doubts as to the relative epoch of arsenopyrite and chalcopyrite, in the Manitoba region of Canada and elsewhere, give place to a certainty in this Matehuala district of Mexico, and there is further established the general sequence: copper, arsenic, zinc, lead. Even the calcite veins by no means represent a process of cementation of fissures by ordinary ground waters, whether hot or cold, but denote the final stage of magmatic invasion. After that, there was absolutely no vein formation, although a fault broke through all the deposits in question, including the calcite, and (as the evidence appears) slowly grew till its vertical element of displacement or faulting reached at least a mile —occupying surely an immense period of time.

The various magmatic invasions, it is pointed out in this paper, obeyed the laws of solutions: passing with ease along tiny rock passages and even through capillary channels to replace earlier formations; but their nature otherwise corresponds with the idea of concentrated solutions which I outlined in Chapter II. Each succeeding invasion of gangue material (lime silicates, quartz, and calcite) powerfully attacked and replaced earlier stages: even calcite, as Dr. Fenner has shown from his microscopic studies, has readily replaced quartz, a process so little to be expected, and so far removed from atmospheric conditions, as to point again my earlier observation that ore deposition is carried on

under conditions of which we have no knowledge and no means of comparison from our experience.

It is shown that the earliest magma solutions which deposited the lime silicates not only deposited no iron or other metals, but removed original iron from the rocks; later the magma solutions became neutral as to iron, neither subtracting nor adding; and finally began to deposit iron, as iron-lime silicates first, and directly afterward as iron sulphides, together with some copper sulphide. The lime-silicate minerals are valuable in showing that this sequence resulted from a falling temperature, for at the stage of copper deposition the earlier pyroxenes gave way to hornblende, a change known, from experiments by physical chemists, to denote a lessened temperature, which is also indicated by the change from lime silicates, previous to the main metallic deposition, to quartz and fluorite, contemporaneous with it.[3]

It is thereby demonstrated that the successive deposition of copper, arsenic, zinc, lead, calcite was accompanied by a falling temperature, and that presumably the critical points of the various crystallizations were thus determined. The earliest magma solutions probably contained iron, which was residual from the alumina-lime-silicate crystallization and passed on upward: the neutral magma solutions, which neither dissolved nor deposited iron, indicate the approach to the conditions favorable to metallic deposition, which were later reached; with the cessation of sulphides (with quartz and fluorite) the lime-carbonate residual solution crystallized (at a still lower temperature); and thereafter vein formation was at an end, for all time. During the earlier (and hotter) stages of mineral deposition, therefore, those minerals which later, with falling temperature, formed

[3] Previous to the ore deposition silica and lime were deposited as the lime silicate, wollastonite; during the ore deposition, as two minerals, quartz and fluorite (fluoride of lime). According to certain experiments, by Day, Shepherd, Allen, White, and Wright, wollastonite is formed (under surface conditions) above 800° C. and quartz below 800°. *Am. Jour. Sci.*, Vol. XIX, 1905, pp. 93-134, and Vol. XXII, 1906, pp. 265-302.

in the same location, and were superimposed on the earlier ones, were probably being deposited higher up, at the zones which temporarily possessed the requisite critical temperature for each.

We are particularly fortunate in having the great post-mineral fault above referred to, which runs through the ore district, and enables us to see into a far greater vertical range of rocks than we could otherwise. On the side of the fault which has been relatively upthrown, and so exposes the deeper zone, the copper deposits are the only important ones (Dolores mine), and the subsequent successive metal stages (auriferous and argentiferous arsenopyrite and pyrite, blende, and galena) become of less and less importance with each succeeding stage, and none are really commercial; but on the downthrown side, which represents the upper zone, the auriferous and argentiferous arsenical pyrite veins are of great commercial importance; the higher-temperature stages (lime silicates and copper) are naturally not represented, and the later stages, consisting of blende and galena, are represented, but (as on the other fault block) are commercially unimportant (Fig. 45, p. 198).

This indicates a definite period of important ore deposition, during which copper was precipitated freely in a lower zone, and, simultaneously, auriferous and argentiferous arsenical pyrites abundantly in an upper zone: and a later brief period of waning ore deposition, during which the various phases migrated downward with the falling temperature.

As to what these temperatures were, we have no accurate data. As mentioned in Chapter I (p. 80), Wright and Larsen's experiments indicate that the quartz of granites and pegmatitic granites crystallized above 575°, and the quartz of pegmatites and pegmatitic quartz veins below that point. *According to this, all ore deposition would take place below 575° C.* Hornblende has been formed by various experimenters around 550°; above 500 to 800° C. pyroxene is formed instead of hornblende. The change

from pyroxene to hornblende took place at Matehuala just at the beginning of the copper deposition. So far as this unsatisfactory data go, the difference in temperature between the gold-quartz vein formation (below 575°) and the copper deposition (500 to 550°) would not be great; but the very approximate nature of these experiments, carried on under surface conditions, is evident.

As to the vertical range of ore deposition, during the most intense period, we have a minimum figure, which is the sum of the vertically developed depth of the copper mine (Dolores) on the upthrown side of the fault, the depth of the argentiferous and auriferous arsenical pyrites mine on the downthrown side (La Paz), and the amount of fault movement: only the minimum movement of the fault is known. This would give the vertical range of the main copper, arsenic deposition as at least one mile, and probably two or more. In the case of the gold-quartz veins we have seen (p. 257) that the minimum range of deposition is a mile, and probably several times as much.

Our record as to the successive overlying zones of ore deposition is usually not a direct one, on account of the fact that mine workings do not as a rule go deep enough to pass from one to the other; and the best record, in many cases, is in the succession of mineral types in a single occurrence, where, on account of dropping temperature, overlying zones of deposition have migrated downward so that different types of veins are superimposed. Occasionally, however, we find in deep mine workings a change with depth, illustrating the change of ore deposition with changing temperature. In Chapter IV, I have described the structure of the dome at Mapimi, on whose flanks very important orebodies occur. The workings of the main mine, the Ojuela, go down in limestone 2,500 to 3,000 feet; at the bottom, drill holes entered coarse alaskite at a depth of about 3,500 feet below the surface, the top apparently flat lying and so the top of a dome-like intrusion. The ores in the limestone are oxidized to a depth of 1,500 to 2,000

feet below the surface: they consist of lead (and zinc) carbonates, iron oxide, silver, probably chiefly in the chloride form, with some arsenic, and a little gold and copper. Earthy-gangue minerals, where present, are quartz and calcite, with some fluorite and barite. Essentially, therefore, the ore is of the argentiferous galena zone, with characteristic accompanying gangues. Below the oxidized zone the sulphide ores are a mixture of blende, galena, arsenopyrite, and pyrite, more or less cupriferous. The sulphides in the lower levels differ from those higher up, since they contain more cupriferous pyrite, arsenopyrite and blende, and less galena. On the bottom level I observed highly cupriferous pyrite running 8 per cent copper. Moreover, lime silicates (which do not occur in the upper part of the mine) form the gangue of the ore on the lower levels, and, as the drill holes show, become increasingly conspicuous up to the alaskite contact in greater depth. What is clearly this same alaskite body approaches gradually to the surface, till it outcrops, a few miles away, in the Viborillas district, and here the associated ores are essentially copper ores, although they contain some lead.

The zones in the Ojuela mine, therefore, are not sharply defined, especially the arsenopyrite zone; but apparently the lower limit of the main galena-blende zone, with its associated characteristic gangues, is reached at or above the bottom of the mine, and from there down comes essentially a copper-bearing zone with lime-silicate gangue. The top of the main lead (silver) zone is also indicated, in this case, as approximately at the present surface, for above it the mountain rises steeply for several thousand feet, and shows numerous mineral veins, but they contain only minor amounts of ore, and are mainly of barren-gangue material. The vertical extent of the main galena-blende zone in this case is about 3,000 feet. In the Aspen district, Colorado, galena-blende ores of this zone occur throughout a demonstrated vertical range of 3,500 feet, without change, and probably the total range was considerably greater.

It is easy to see how even the main stages of metal and gangue deposition may be locally mingled, due to fluctuating temperature, with the resultant formation of complex ores; nevertheless, the distinctions and successions are often surprisingly sharp and delicate. Note, for example, the celestite (strontium carbonate) veins at Matehuala, which are large and important, and belong in the general calcite-vein period. After their formation they were split open, and the new fissures were filled with calcite. Here we have a quite unusual refinement of selective precipitation. More commonly, and in many districts, calcite veins were preceded by veins of brown mixed carbonates of lime, iron, manganese, and magnesia, which contain small amounts of metallic minerals.

The case of the ore deposits in Velardeña, in Durango, Mexico, is one of unusual interest. It represents the copper, arsenopyrite, zinc, lead, silver sequence. It has been made the subject of careful study by myself and assistants, and a paper thereon has been published by myself and Mr. Garrey.[4] While the phenomena are somewhat more complex than at Matehuala, they are none the less convincing, pointing, as they do, to many conclusions. The results are a corroboration of those at Matehuala, as we shall see. The district is quite extensive, but for the sake of simplicity only the ore deposits in a single range (the San Lorenzo range) will be alluded to (see p. 200). In this range there were intrusions of dioritic rock into limestone—neck-like protrusions upward, of varying size, representing the exploring, upward-groping fingers of the magma below.

This intrusive diorite magma shows a high degree of differentiation, so that of the three chief intrusions one neck is more siliceous, or predominantly granitic (Copper Queen intrusion); another predominantly dioritic (Guardarraya intrusion); and the third predominantly diabasic (Terneras intrusion). Gradations are found in each, and that they represent variations of a single magma is indubi-

[4] *Econ. Geol.*, Vol. III, No. 8, 1908, p. 688.

table. In other words, a gradual change is freely exhibited from an augite diorite of diabasic aspect to granitic phases. In the dioritic phases, hornblende is the predominant dark mineral; in the diabasic phases, augite; and in the granitic phases, mica. That augite has in part at least been formed by alteration of hornblende is shown by numerous pseudomorphs of augite and magnetite after hornblende; and that mica has in part also been derived from hornblende is shown

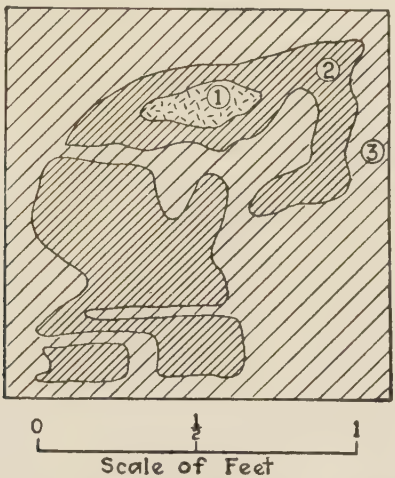


FIG. 54.—Matehuala, San Luis Potosi, Mexico. Cobriza mine. Sketch showing alteration of monzonite to lime silicates. 1, Residual monzonite; 2, pale-green pyroxene rock, derived from alteration of monzonite; 3, coarse red garnet-vesuvianite rock, derived from alteration of 2.

also by pseudomorphs. This suggests that in the original magma hornblende was the first ferromagnesian mineral to crystallize, and hence that the magma was an intermediate one—a diorite or monzonite, such as was typical, at this period, of the whole petrographic province of Mexico and the western United States. The differentiation into distinct phases appears to have taken place before intrusion, for the various intrusions have taken place at the same period.

All of the intrusions were followed by metamorphism,

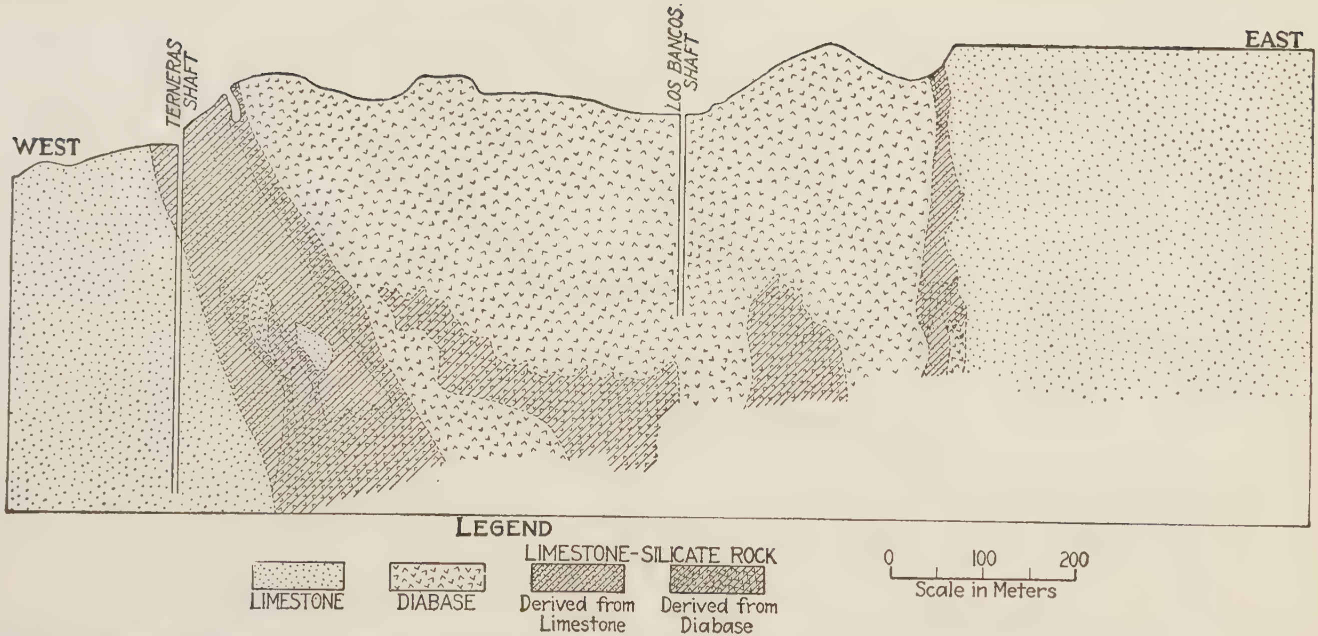


FIG. 55.—Section on plane (nearly vertical) of Terneras vein, Velardeña, Mexico, showing metamorphism of wall rocks, accurately mapped from complete exposures by mine workings (not shown). Lime-silicate rocks of similar appearance and composition are derived from limestone and diabase alike, but residuals and transitions betray the origin. A study in "contact metamorphism."

consisting especially of the formation of lime silicates, particularly pyroxene and garnet. These minerals have replaced limestone and the intrusive rocks alike, as they have at Matehuala (Fig. 54); in fact the amount formed by replacement of the igneous rocks has been locally greater than that formed by replacement of the limestone (Fig. 55).

In the San Lorenzo range there are ore deposits associated with the igneous necks and the lime silicates. While in general like those at Matehuala, they are, like the igneous rocks, more clearly subdifferentiated and localized.

The most basic of the three intrusive areas is cut by regular parallel veins, which are later than the lime silicates. These veins show entirely different and sharply separated stages. The earlier veins were repeatedly split open, and new types of vein material deposited, making *compound veins.* One of the most striking features brought out is that a given period of vein formation appears to have lasted only a short time, and is a definite point of geologic history, comparing in exactness and clear definition with the intrusion of an igneous rock.

In the principal vein—the Terneras—the following successive stages of metal deposition are shown:

1. Cupriferous sulphide (and quartz). Chief copper period.
2. Galena and blende. Chief lead and zinc period.
3. Argentiferous and auriferous tetrahedrite. Chief silver period.

The period of deposition of cupriferous pyrite followed the main lime-silicate period, but there is some silicate gangue in its early stages. Ordinary gangue materials consist of quartz and mixed brown carbonates (of lime, magnesium, iron, and manganese); some of these are later than the main metal deposition, and show crustification or banding; and last of all, as at Matehuala, are large and barren veins of calcite.

Some of the veins of this basic intrusive area contain auriferous arsenopyrite and some jamesonite (lead-anti-

mony sulphide). The relative position of the arsenopyrite-jamesonite deposition is not established in this district, other than that it is closely connected with the cupriferous pyrite.

In the case of the granitic intrusive neck (the Copper Queen), the general mineralization and stages seem the same, although not so clear; the sulphides, instead of occurring along regular veins, form pipes near the contact of intrusive rock and limestone. More copper also is deposited here, so that the principal values are in copper, while in the Terneras veins gold and silver values are predominant. While the Copper Queen orebodies are typical of what have been termed "contact-metamorphic" deposits (see Fig. 102), and the Terneras type are typical regular veins, yet it is clear that the two types are variations of a single group, and closely allied, both mineralogically and in every other way.

In general, I feel that the term "contact-metamorphic" ore deposit should be abandoned, or used with great care. It has been used to designate irregular orebodies with lime-silicate gangue, on or near the contact of an igneous rock, usually intrusive into limestone. But I have shown in these cases at Matehuala and Velardeña that these deposits are not a special type, as far as metal contents and sources of metals go, but follow the regular rules of magmatic ore deposition; and that in the presence of limestone, or other source of lime, and above a certain temperature, the attendant or gangue minerals are lime silicates, while below that temperature they would be quartz and calcite. I shall presently show, moreover, that this lime-silicate gangue may accompany ores deposited in regular fissure veins. Moreover, at Matehuala, I have shown that the apparently typical contact ores really occur, as a rule, along definite fissure channels, or veins, localized frequently along or near the igneous contact (with limestone), for physical reasons; and this is often the case elsewhere.

The parallelism of occurrences in different districts like

Matehuala and Velardeña is not a rough one, without fixed and definite conclusions; but a correspondence of sequence so minute, so regular and orderly, as to indicate a general and fixed law.

In the Velardeña instance the reader may note that a new stage of metallic deposition, not detected at Matehuala, is present and of importance: the stage of argentiferous (and auriferous) tetrahedrite, which constitutes the chief silver-bearing stage, and follows the galena and blende (the chief lead- and zinc-bearing stages), and precedes the barren-gangue stages. This is an important and regular stage in the sequence of metal deposition.

I think I have now sufficiently pointed out the magmatic origin of these copper deposits and the succeeding stages of arsenic, zinc, lead, silver, barren gangue, deposition; and their relation to igneous intrusions of which they represent the final phases. I will now describe a similar sequence of metal deposition, where the magmatic origin is not locally demonstrable, and where no lime silicates immediately precede the metallic stage. But we have reached the stage of demonstration where it is safe to assume the magmatic origin, for the other features, as will be seen, correspond faithfully.

The Angangueo mines, in the State of Michoacan, Mexico, have been worked for over a hundred years. The country rock is an andesite, probably of Tertiary age; and the veins are perhaps younger than those of Velardeña, Mapimi, and Matehuala, where there is evidence of greater erosion. Nevertheless, as will be seen, the sequence of metal deposition is nearly the same.[5] The ore deposits of Angangueo are nearly vertical veins, regular and very persistent. The ores were deposited as sulphides, with earthy-gangue minerals. From the time when the vein zones were first formed in the andesite, till a very much later period, the fissures were intermittently reopened. Not all the fissures were originally opened at the same time, and not all neces-

[5] The field studies at Angangueo were made by myself.

sarily took part in each successive reopening. During the lapse of time which covered the various periods of fissure opening, the nature of the ascending solutions which entered these fissures gradually changed. Thus we have a considerable variety of vein material, and the interrelations of these different types of material are such as to record marked differences of age. The sequence was as follows:

1. Pyrite and cupriferous pyrite.
2. Blende.
3. Galena (argentiferous).
4. Quartz veins, carrying silver.
5. Carbonate of manganese (rhodochrosite).

Quantitatively all the above stages are well represented; and there are transitional stages, showing a continuously developing sequence. The first three stages have little gangue, while gangue material (quartz) is predominant in the fourth, and the fifth has practically no metal. The different types of vein material are frequently distinct enough to be mined separately—No. 1 for example, as a copper ore, and No. 4 as a silver ore.

This series corresponds with that at Matehuala and Velardeña, except for the arsenopyrite phase, which was not noted. This arsenopyrite stage is frequently obscured in various ore districts, now appearing strongly, again being hardly represented, if at all.[6]

It will be seen that the chief silver-bearing stage, which at Velardeña follows the chief lead-bearing stage, and is very important, is also present and important at Angangueo. At Velardeña, the chief metallic mineral (always in small quantities as compared with the quartz gangue) is argentiferous tetrahedrite (copper-antimony sulphide). At Angangueo, primary argentite (silver sulphide) is present at this stage: also stephanite (silver-antimony sulphide).

The brown mixed carbonates of lime, iron, manganese, and magnesium, which at Velardeña immediately succeed

[6] See Chapter XIII, p. 615.

the metal-bearing stages, are represented at Angangueo by manganese carbonate; although there is some siderite, it is slightly later, indicating, like the strontium carbonate (celestite) of Matehuala, an especial refinement of selective precipitation.

I will now proceed a step further, and describe an instance where the mineral succession is shown, not in the same mine or in the same vein, but by a change from the center to the periphery of a mineral district; and this instance is also remarkable, for showing, strikingly, lime silicates as gangue for a regular fissure vein, and for other reasons. In fact, when I look over the situation before attempting to describe it, I come to the conclusion that it affords one of the strongest instances of principles covering the problems of magma intrusion, which I have discussed in the third and fourth chapters.

The occurrence records the copper, zinc, lead, silver sequence.

In the State of Aguascalientes, Mexico, the mining districts of Tepezala and Asientos lie within a few miles of each other and in the same group of hills. The Tepezala district occupies the chief elevation, and is marked by a group of isolated hills. The Asientos district lies further down, on the slopes of the same group of hills. The oldest rocks of the region, which form much of the portions of less relief in the central part of the hill group, are thin-bedded limestones, with interstratified limy shales—part of the thick Mesozoic series which covers all this portion of Mexico.

The sedimentary rocks have been broken through, presumably in Tertiary time, by volcanic rocks, of rhyolitic, trachytic, and andesitic character. These are now represented by volcanic necks. They were also deposited on the surface, as flows from the volcanoes whose conduits of ascending lava are now represented by the exposed necks, and as beds of volcanic tuff, made up of the showers of debris resulting from explosive eruptions. During the long

period since these volcanoes were extinct, erosion has been active, wearing down the center of volcanic eruption, which originally must have towered far above its present level; also stripping off with relatively greater speed the softer shaly limestones, and leaving in relief the harder portions. Thus the volcanic necks now stand up as low peaks. At Tepezala, where these volcanic necks are conspicuous, erosion has entirely removed the surface volcanics; but they still exist at Asientos, where horizontal or slightly dipping tuffs and flows remain.

What appears to be the main volcanic center of this group, at Tepezala, has been carefully mapped (with transit, by myself and my assistant, Mr. Anderson), and a reproduction of the map is given in the illustration (Fig. 56). Within this restricted area there are three volcanic necks, lying close together, and so grouped, as will be seen, as to suggest derivation from a common source below. The diameter of this whole field (containing the three necks) is about half a mile.

It has been found that the necks are of different age, and represent three successive periods of outbreak. The central, or largest one, is the oldest; to the south, the smallest is intermediate in age; and on the north is the youngest, now most conspicuous in the topography, and forming the elevation called San Juan Mountain. The oldest, or main neck, is older than the ore deposits of the district; the youngest (San Juan Mountain) is more recent than the mineralization; while the intermediate intrusion seems more nearly contemporaneous—the ore deposition seems to have followed upon its arrival.

The first volcanic neck, together with the intruded limy shales in its vicinity, was subjected to stresses after its injection, which reduced both volcanic rock and shale to a more or less schistose condition. So considerable has this been that it is often difficult to distinguish whether the altered rock was originally shale or "porphyry." On the surface the difficulty is not so great, since the weathering

brings out the characteristic light color of the "porphyry," so that it has always been recognized as such by the miners:

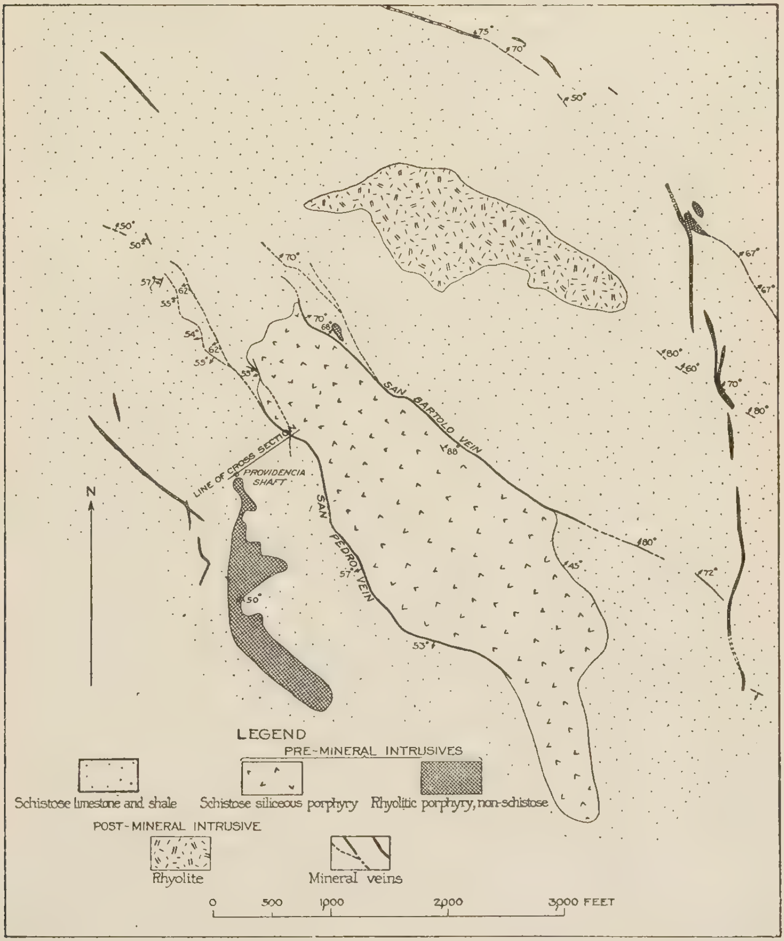


FIG. 56.—Surface geology at the mining camp of Tepezala, State of Aguascalientes, Mexico. Shows volcanic necks of three different ages. The oldest has been rendered schistose, and subsequently uplifted between two normal faults, which have later become fissure veins, with filling of copper sulphides and lime silicates. By J. E. Spurr and Alexander Anderson.

but underground it is not so plain. The porphyry schist is more resistant to erosion than the calcareous-shale schist,

and hence stands out in moderate relief as a hill; but the alteration has been so complete that the microscope can only establish it as siliceous and fine grained—a rhyolitic rock. The intermediate intrusion is also rhyolitic, but shows biotite; and the last intrusion is a very siliceous rhyolite (the equivalent of the quartz-feldspar, or alaskite magma).

The schistosity seems to be local: I have not mapped it in detail, but from what work was done it appeared to me to be confined to this central area. At Asientos the shales do not show it. It is not the result of regional stress and movement, for nowhere else in Mexico have I noted the rocks of this period similarly affected: nor, indeed, have I noted schistose development elsewhere in all this part of Mexico. It coincides, apparently, as to general area, with the field of volcanic neck intrusion; and I can only explain it as due to the pressure (with resultant flowage and recrystallization of both shale and rhyolite) of subsequent local magma movements—very likely that of the uprising igneous column at the base of the earlier-solidified plug.

In Chapter III, the frequent formation of schistosity in overlying rocks as the result of slow upwelling of igneous magma below has been argued; and in Chapter IV, local long-continued and slow uplifts, such as those at Aspen, in Colorado, and Matehuala, in San Luis Potosi, Mexico, were discussed, as due to the upward movement of a *column* of magma. At Aspen the assumed magma plug is not exposed, but the evidence led to the conclusion that it had been slowly rising "during the whole of the Tertiary period, keeping pace with a considerable degree of fidelity to the stripping of the cover of the dome by erosion." At Matehuala, we have the igneous plugs exposed, and these plugs, with the surrounding invaded shales and limestones, have been subjected to a steady upward doming, over what has been interpreted as a long period of time, during which the fissures in the rock became more and more open, as if under less and less gravity pressure: a circumstance which was similarly observed at Velardeña and elsewhere, and led to

the belief that the uplift, and the rise of the magma column below, here also kept pace more or less with the stripping off of the weight of overlying rocks by erosion.

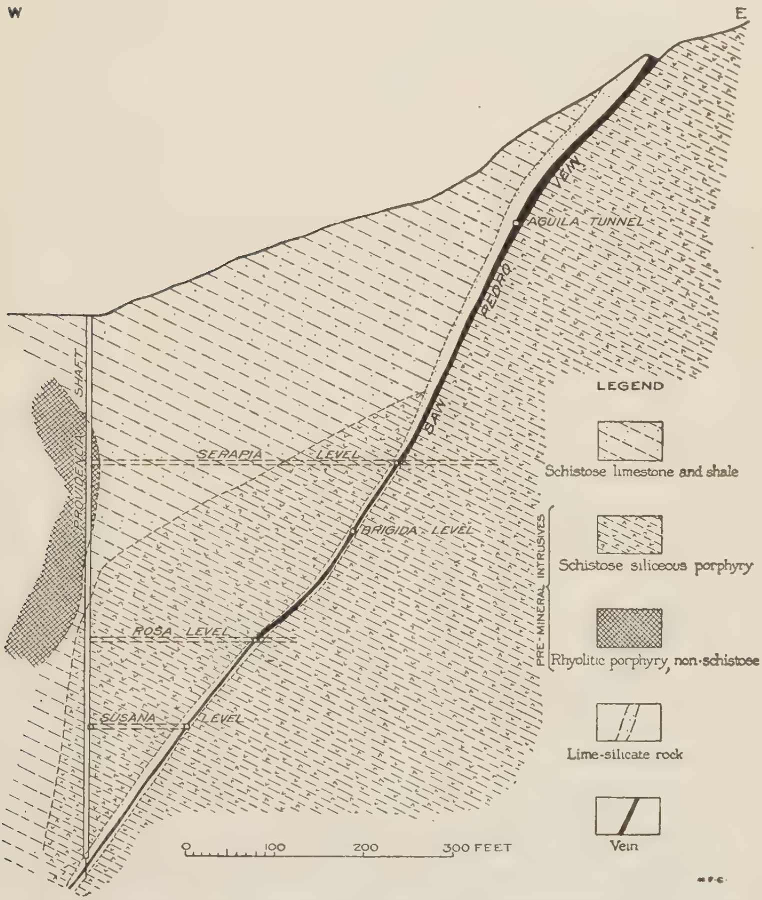


FIG. 57.—Cross-section of San Pedro vein at Tepezala, State of Aguascalientes, Mexico. See Fig. 56, preceding. By J. E. Spurr.

That the magma at the base of the solidified volcanic plug at Tepezala did continue to rise during this period of schistosity is shown by the appearing of the second rhyolitic neck, shown in the map just south of the original (and largest) rhyolite neck. This second neck was not affected

by the shearing. This second column came up, it is seen, on the flank of the original column. But a stranger thing has happened. The original column, after having been sheared profoundly by subsequent stresses, has been uplifted as a block between two parallel faults which now determine its opposite (northeast and southwest) boundaries. These are both normal faults, dipping in opposite directions (about 60°) away from the schistose neck. The section shown in Fig. 57 gives a local measure of the minimum of uplift as about 500 feet. Where the fault fissures pass beyond the ends of the schistose neck, they branch and disappear; therefore, the upward movement was essentially confined to the neck itself. While this would indicate, as in the other localities to which I have referred above, the pressure of unconsolidated magma at the base, it is astonishing to find this operation in the present case, where the high degree of schistosity induced in the solidified plug gives it (deceptively) a most ancient appearance. Indeed, on this very account, this Tepezala occurrence has been described by a Mexican geologist as an ore deposit in the pre-Cambrian, and so published in the records of the Mexican meeting of the International Geological Congress. It is cases such as this that made me resolve, in writing this book, to stick, so far as possible, to my own observations. It is work enough to run down and correct one's own errors, but at least one has the background therefor; in the case of the errors of others we have not that advantage.

This period of uplift of the oldest plug was the period of surgence of the second volcanic neck, which now outcrops to the south. This is shown by the phenomena of mineralization, for the fault fissures above mentioned have been penetrated by ore-magma solutions and have thus become the chief veins of the district, and this same mineralization followed (apparently immediately) the intrusion of the rhyolite of the second period, as may be observed where this rhyolite outcrops sporadically, in lesser necks and dikes, in this vicinity. The character of the rhyolites of these

three periods is sufficiently different to be recognized wherever they occur, the second period having less quartz, and being of a monzonitic or trachytic type, and the third being very siliceous.

The third rhyolite neck (that of San Juan Mountain, on the north flank of the original neck, or on the side opposite to that of the second neck) was later than all mineralization; it is perfectly fresh and unaltered, and some of the mineral veins are cut by later dikes of this rhyolite. At Asientos, where the surface lavas come in, the veins occur in a dense trachytic lava flow which is probably of somewhat the same age as the second period of rhyolite intrusion at Tepezala; and they are capped by a barren siliceous rhyolite flow, later than the mineralization and similar to the San Juan volcanic plug.

The veins at Tepezala—the San Pedro on the southwest contact and the San Bartolo on the northeast—are remarkable in that, although fissure veins of great regularity, they have a lime-silicate gangue, which is confined to the vein precisely as quartz is in the usual fissure vein, and does not characterize the wall rocks; nor, indeed, was it noted elsewhere in the district. The lime silicates are dark-green pyroxenes and garnets, evidently iron-rich, and therefore corresponding to the hedenbergite and andradite which were formed in the Dolores mine, at Matehuala, at and immediately before the beginning of copper-sulphide deposition. At Tepezala, as at Matehuala, copper-bearing pyrite is the chief metallic mineral. There is also a quartz and calcite gangue, with which the copper-bearing pyrite is more closely associated than with the pyroxene and garnet; and thus the correspondence with the phenomena at Matehuala, Velardeña, and elsewhere is complete, showing the copper deposition to have begun at that critical stage of lowering temperature when lime silicates gave way to quartz and calcite. Further remarkable is the evidence, which I noted in the mine, of the deposition of the vein material, including lime silicates, quartz, calcite, and sulphides, largely in fis-

sures. The pyroxene occurs in long sheaves of slim crystals, perpendicular to the walls—almost the structure called "comb-structure" in quartz veins, in fact. Moreover, a rude but unmistakable banding is everywhere exhibited, showing lime silicates and sulphides near the walls of the vein, and surrounding inclusions of wall rock where the vein contains these (as it does in places); and, within this, quartz-calcite filling, carrying more abundant sulphides.

In that these ore deposits are copper ores associated with lime silicates on an intrusive contact, they fall into the empirical class of "contact-metamorphic" deposits. In the case of many of these, as at Matehuala, Velardeña, and elsewhere, I have demonstrated the fact that the lime-silicate formation was later than the intrusion, and not attendant upon it, as the current theory assumes; but the development of a high degree of schistosity between the intrusion and the "contact metamorphism" was startling even to me. That these lime-silicate ore zones, where they occur on the igneous contact in the Dolores mine, at Matehuala (as well as at Descubridora, p. 645), do so occur largely because of the formation of fissure zones along the contact was explained above; and the main difference in this regard between Matehuala and Tepezala is that while in the former place the copper veins, although they followed fissures, did not form in open fissures, those at Tepezala are believed to have done so. Indeed, the indicated openness of the Tepezala veins (which, as shown in the cross-section of the San Pedro vein (Fig. 57), are 15 to 25 feet wide) is only comparable with that of the barren calcite veins at Matehuala and Velardeña, which form the last of the magmatic vein series. In these districts, it was believed that the gradually increasing width of fissure, as the magmatic vein stages succeeded one another, indicated a decreasing gravity pressure, and hence a lessening of the overlying rock load by erosion.

According to this clew, the Tepezala copper veins were formed at the same temperature as the Matehuala and

Velardeña copper veins, but at less pressure, and closer to the surface. Their geological association, occurring as they do at the roots of Tertiary volcanoes, would support this conclusion, since we usually conceive of this horizon as more shallow than that of the immediately post-Cretaceous intrusions. The relative texture of the rocks is also a similar indication, for while at Matehuala and Velardeña this is granular, indicating cooling under moderately deep-seated conditions, at Tepezala the texture is fine grained and dense, showing relatively rapid chilling, nearer the surface.

Fissures of the width indicated for the Tepezala veins, or, indeed, for the calcite veins of Matehuala, could not, of course, have remained open if empty: it is indicated that at the existing gravity pressure the telluric pressure of the vein-forming solutions was sufficient to hold the fissures open against the force of gravity and other forces while the vein materials crystallized—not by a sudden freezing, as seems to be indicated in many veins, but by a more leisurely crystallization. It is to be noted, nevertheless, that the Tepezala veins are one-stage veins—they have not been split open and refilled by any of the various stages normally succeeding. In this case again, as in the case of the Griffith mine, at Georgetown (Chapter II, p. 144), it is shown that banding or crustification in a fissure vein is not necessarily evidence of filling of an empty fissure by circulating waters; the vein filling was, on the contrary, accomplished in these cases by concentrated ore magmas forcing open fissures and crystallizing in quiet thereafter. The banding indicates gradual crystallization; the more common homogeneous type of fissure filling, quick freezing.

As to the relation of vein filling to wall rock, we find at Tepezala throughout the veins the same lime-silicate gangue and other vein materials, whether both walls are of igneous rock, whether one is igneous and one sedimentary, or whether both are of sedimentary rock.

While there was only one main stage of mineralization—the main copper stage—at Tepezala, as we go away from

this volcanic center we find veins which were apparently formed contemporaneously (since they are all connected with and later than the second volcanic intrusion, and older than the third), but which show stages characteristic of a lesser temperature. About a mile west of Tepezala is the Victoria Negra group of veins, where the gangue is mainly quartz and calcite, although lime silicates occur on the margins of the veins—the reverse proportion to that at Tepezala. Also, the principal ores are galena and blende (which occur at Tepezala, but in subordinate quantity); while the copper sulphides, although common, are relatively subordinate. About the same distance east of Tepezala is

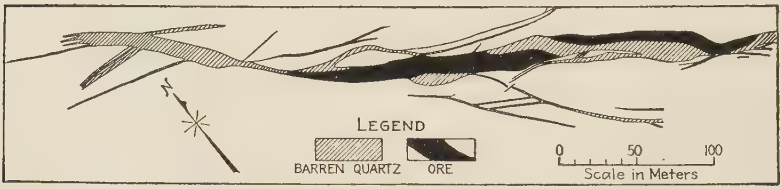


FIG. 58.—Santa Francisca vein, Asientos, Durango, Mexico. Horizontal plan on second level. Main vein occupies a fault fissure in trachyte overlying shale. Shows vein of "linked" and branching type, following fissures formed near the surface; also distribution of pay-ore.

the Pañuela vein, even more markedly a silver-lead vein than those of the Victoria Negra group, with practically no lime-silicate gangue, but containing quartz and calcite, and still a little chalcopyrite. This vein has been reopened, and the fissure filled by later rhyolite.

Finally, in the Santa Francisca mine, at Asientos (Fig. 58), we have a great vein with a quartz gangue and values mainly silver. This vein also carries much galena and blende.

The sulphides in the Santa Francisca vein are less abundant, however, than in the other veins described, quartz being the chief filling. The vein occupies a strong, wide fault fissure in a siliceous lava flow. This flow overlies shale, into which the vein has been followed in depth, and underlies rhyolitic flows, which are younger than the vein

and correspond with the San Juan or third intrusion at Tepezala. The Santa Francisca vein, like the Tepezala veins, is wide and well banded. The layers parallel the vein walls, indicating that much of the material was deposited in open fissures, as at Tepezala. The vein frequently comprises several distinct parallel bodies, separated by altered country rock, and the total width in places may be as much as 40 or 50 feet. The vein strikes northwest, like all the veins described, and appears contemporaneous with all the rest.

In other words, we have in this Tepezala-Asientos district a series of simple veins, none of which show clear-cut successive stages within a single fissure, but each of which substantially marks a single stage of vein deposition; and all were apparently formed at practically the same time. In the center of the district, which apparently represents the deepest zone at the period of mineralization, we have the chief copper stage; on the flanks this passes into veins of the predominatingly lead-silver stage; and on the margin to the Asientos vein, predominatingly of the principal silver stage; the stages apparently depending on relative temperature at the period of mineralization, it being hotter in the center (and at that time most deeply buried portion) of the district, and cooler on the shallower margins.

At Tepezala-Asientos, therefore, we have the same succession of minerals as at Angangueo, but in the former case more distinctly segregated into separate veins: copper, zinc, lead, and silver. As at Angangueo, the arsenic zone of Matehuala was not noted at Tepezala-Asientos.

We have now seen that in many districts whole or partial sequences have been observed which admit of close correlation, and represent a regular law of sequence of metallic deposition. The stages, as I view them now, are substantially as I outlined them in 1912, and which I may briefly repeat here: A, the pegmatite or pegmatitic quartz zone, containing molybdenum, tungsten, etc.; B, the free gold auriferous pyrite zone with coarse quartz gangue; C, the cupriferous pyrite zone (principal copper zone); D, the

zone of argentiferous pyrite and auriferous arsenopyrite, with sometimes jamesonite, etc.; E, the blende zone (principal zinc zone); F, the galena zone, often argentiferous (principal lead zone); G, the zone of high-grade and often complex silver-bearing minerals, including especially tetrahedrite and tennantite (gray copper), as well as other sulpharsenides and sulphantimonides, accompanied characteristically with much quartz.[7]

We shall find the above sequence or parts of it in so many places that we cannot doubt as to the general applicability of a law.

The lowest zones—such as those in or closely allied to pegmatites (molybdenum, tungsten, etc.) and the gold-quartz zone, will be best developed in rocks which have crystallized in depth—the plutonic holocrystalline bosses, stocks, or masses of granite or other igneous rock, whose holocrystalline texture, habit of occurrence, and frequent exhibition of internal differentiation phenomena indicate the considerable depth below the surface at which the ore-making episodes occurred. The copper stage is also very characteristically associated with these older rocks, but not in all cases; for in some regions, as, for example, apparently in the gold-quartz veins of Nova Scotia and Australia, which belong to the deep-seated type, the overlying copper zone, if it originally existed, has been eroded away.

On the other hand, in the case of the rocks commonly, though not accurately, called intrusive rocks (for possibly all the igneous rocks except the surface lavas, which are exposed to our view by erosion, are intrusive), the conditions have been different. I refer to the rather finely holocrystalline or porphyritic rocks which in the form of plugs or dikes

[7] It is only in the last division (G) that I have here departed from the classification of 1912; and the difference is that in the present scheme I am tempted to pass over lightly, or to omit, the gold that I included in my classification of the date referred to. I am disposed to do this for reasons which I will dwell on later, in considering the origin of the Tertiary bonanza deposits, which I formerly included in group G, but which I now believe should be interpreted as a composite group in which the gold belongs largely to a special shallow-formed zone (see p. 300, Chapter VI).

or irregular intrusions have penetrated further up into the crust than have the characteristic plutonic bosses or stocks, and consequently have solidified at a cooler horizon. These rocks typically do not show marked internal differentiation phenomena. They probably represent the advance guards or upper tentacles of larger masses below, which masses correspond with the plutonic bosses.

In connection with such finely holocrystalline or intrusive rocks, we find the A and B zones (the pegmatitic and gold-quartz veins) usually scantily, if at all, represented. This is the principal zone of the copper deposits; and only by much deeper erosion would the full natural strength of the underlying zones be encountered. In other words, it is evident that in these localities the initial temperatures (because at any one horizon, such as is now exposed by erosion in any of these districts, it is clear that a succession of mineral deposits supervening on one another is mainly a question of differences of temperature and not so much of pressure) necessary for the development of the lower zones of ore deposition were too briefly sustained for a strong representation of these zones to be accomplished, if indeed any at all; while the temperature and pressure zone being the most favorable one for copper, great and important deposits of this metal are developed under these conditions. Nevertheless, the lower zones are frequently represented (though weak) under these conditions, as at Helvetia, where the gold-quartz stage is represented, though unimportant (pp. 84, 310).

In these predominantly copper deposits the overlying zones, like the blende zone and to a less extent the galena zone, are characteristically better represented than the normally underlying zones, because the requisite temperature for the formation of these overlying zones normally has supervened with the falling temperature incidental on crystallization, consolidation, and cooling of the igneous intrusion which has supplied the heat; so that if this fall takes place during the critical and relatively brief (though

variable) period of ore deposition, the upper zones—of lead and zinc—migrate downward, and are superimposed upon the earlier-formed copper zone. This is a very common and characteristic occurrence, and is exhibited at the typical copper camps mentioned—at Matehuala, Velardeña, and Helvetia.

It is very likely due to this process of downward migration and superposition that blende ores, or even those of galena, become occasionally so intricately associated with those lime silicates which have formed by replacement and alteration near igneous intrusions, that their contemporaneity has been taken for granted, and they have been described as "contact-metamorphic" deposits of blende, etc.

Where there are no such phenomena of superposition, this circumstance indicates a sustained equable temperature during the critical period of ore deposition. This is evidenced, for example, at Tepezala-Asientos (as described above), where the formation of the characteristic metal sulphides in their normal and characteristic successively overlying zones is shown, but there is no evidence of downward migration and superposition.

This latter condition demonstrates how relatively brief, after all, is, on the average, the critical period of ore deposition or injection.

The largest deposits of zinc and lead, again, have usually formed in their characteristic zone, higher up than the main copper zone. The associated igneous rocks (as at Leadville, Aspen, Breckenridge, and Georgetown, in Colorado) are characteristically finer textured than those associated with the major deposits of copper; they are characteristically rather fine-textured porphyritic rocks. The typical "porphyry" is associated with these: granular igneous rocks associated with them are the exception to the rule. And internal differentiation phenomena in the rocks are characteristically altogether lacking.

Here again we find the normally underlying zones of ore deposition sparingly represented, if at all, for in most cases

the sustained temperature never has been high enough to allow the deposition of copper, for example; but the overlying chief silver-bearing zone, with its characteristic rich sulphides, sulphantimonides, and sulpharsenides, and accompanying gangue of (mainly) quartz, is frequently abundantly represented, through the process of downward migration and superposition during metallization. This combination is well shown at Aspen and at Georgetown, in Colorado.

In the case of the blende-galena ores, the elevation of the principal zone of deposition is such that the ores are often found overlying (by a considerable distance) a related intrusive plug or dome; and the igneous rock is not exposed to mining operations, a condition which occurs far oftener than in the case of copper. Such is the case, for example, with the zinc and lead deposits near Monterey, where only the punching up of the limestones into small characteristic abrupt domes indicates the underlying igneous plugs. At Mapimi, as has been described, the igneous dome underlying the great silver-lead deposits has been found, by drilling only, at a depth of 3,000 feet. Thus, the usual lack of igneous rocks in connection with the lead-zinc deposits in the Mississippi valley and elsewhere in the world is not a proof that they are of non-magmatic origin; indeed, it harmonizes with their known general conditions of formation.

The rule, therefore, is, apparently, for those typical and orderly cases which enable us to discern the law of ore deposition, that with a given predominant ore zone, as for example of gold, of copper, or of lead and zinc, the underlying zones will be represented only slightly or not at all, at the erosion plane exposing the principal metallization zone in question; but the overlying zones are, frequently, definitely represented, through migration attendant upon the normal process of cooling.

If, therefore, having fully determined some of the main zones of ore deposition, we find that the typical sequence

is reversed, and that, for example, a lead-zinc metallization has been followed by a copper metallization, the inference is that this series was deposited during a critical ore-deposition period signalized by a rising temperature instead of the normal falling one. The examples of this inversion of sequence are far too common to be phenomenal; and, therefore, they teach us much concerning intrusion. Since the temperature is clearly derived from the igneous magma, a rising temperature, as registered by the mineral sequence, indicates that the intrusive plug or dome continued its upward intrusive course during ore deposition, so that a normally underlying zone migrated upward and was superimposed upon a normally overlying one.

An excellent example is the ore deposition at Aspen, a district which has already been discussed on account of the evidence of the growth of a local dome from near the close of the Cretaceous down to the present time (p. 190). The ore deposits are grouped around, above, and near this dome so as to indicate their connection with the hypothetical igneous plug below.

There are two very important classes of ore. One consists of rich silver ores containing sulphides, sulphantimonides, and sulpharsenides of silver, or of silver and copper, including polybasite, argentite, tetrahedrite and tennantite. This is the typical mineralization of zone G (p. 284). The other class of ores consists of galena (very low grade with respect to silver) and blende. This is the typical zone E-F. Barite veins are associated with the rich silver ores. My study[8] shows all to be primary, with the following sequence:

1. Barite.
2. Silver sulphides, sulpharsenides and sulphantimonides.
3. Galena and blende.

In this case the evidence (contained in the inverted sequence) of ore deposition during a period of rising temperature checks up with and corresponds with the inference as to a rising plug of magma, reasoned out from the slow

[8] *Econ. Geol.*, Vol. IV, pp. 301-320.

growth of the dome, with attendant faulting, during and after ore deposition; but it is evident that the temperature never reached so high, during the ore-deposition period, as to cause the upward migration of the copper zone to the plane now exposed by erosion.

A very fine example of reversed sequence is shown in the Tiro General mine, at Charcas, State of San Luis Potosi, Mexico, not many miles from the Matehuala copper mines, to which I have so often referred. At the Tiro General mine, Mesozoic limestones and shales have been intruded by alaskite or granite porphyry. The Tiro General vein occupies a strong fault fissure which has formed at the porphyry contact, though it locally cuts into the porphyry on both walls, or into limestone on both walls. The cause of the fissure was, at least partly, and probably wholly, due to a slipping down or sagging of the porphyry after intrusion, such as is characteristic of many intrusions.

The first fault fissure along the contact had a vertical movement of about 50 meters; and, probably directly after its formation, was occupied by a vein of dark zinc-blende, with some argentiferous galena—representing, therefore, the E stage of ore deposition. This vein was developed at the time of my examination down to 440 meters below the surface. A continuation of the sagging of the porphyry produced a further faulting, with a vertical movement of some 80 meters. The new fault in part followed the old one (which had been occupied by the blende vein), and in part diverged from and ran parallel to it, with country rock between. The new fissure was filled, apparently at once, by a vein of copper ore, consisting of quartz carrying chalcopyrite and cupriferous pyrite, with some pyrrhotite (Fig. 59). Therefore, where the successive fault fissures coincide, the present vein is a mixture of the zinc and copper ores (a compound vein); but where the fissures are separate, the veins are altogether and strikingly distinct in type. The order of the deposition of these two stages is the reverse of that at Matehuala, and that usual elsewhere, and indicates

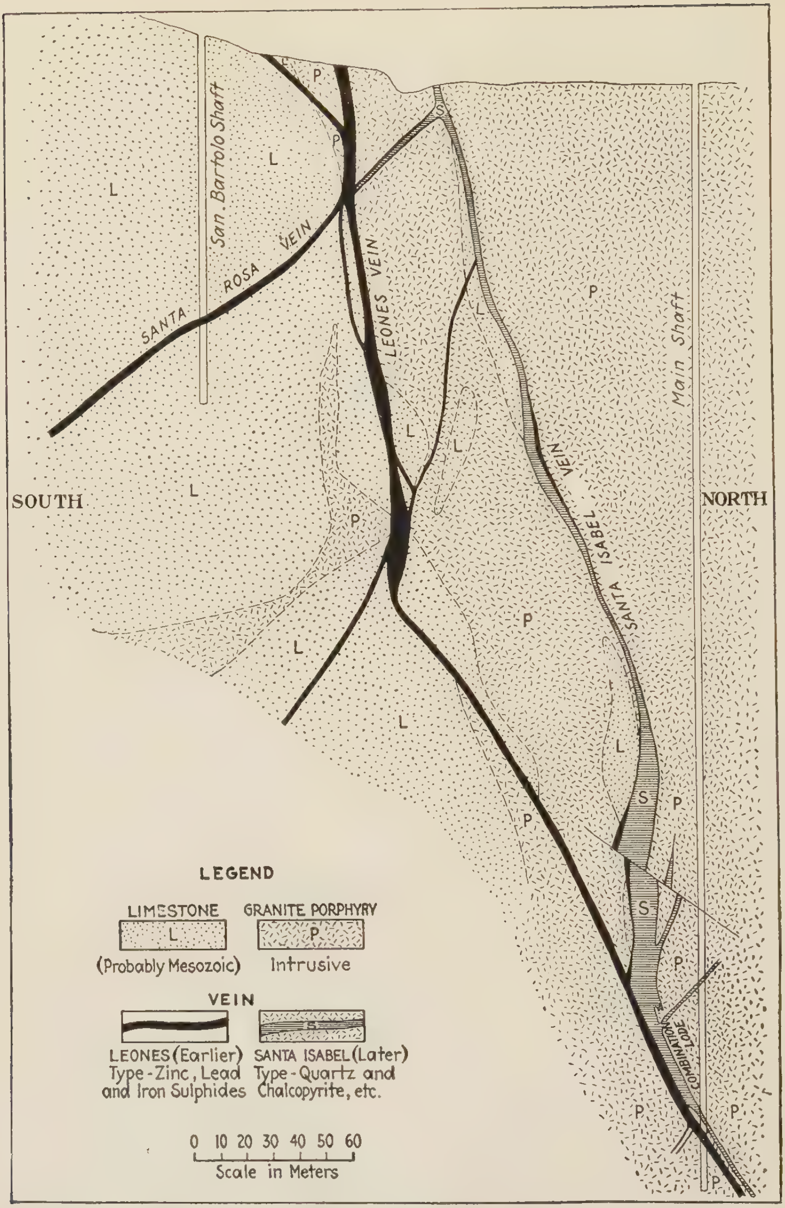


Fig. 59.—Cross-section through Tiro General shaft, Tiro General mine, Charcas, San Luis Potosi, Mexico. Shows two sets of veins. 1, The Leones type; sulphide veins, with blende, galena, and pyrite; first formed. 2, The Santa Isabel type, of quartz and chalcopyrite; formed later. At the bottom the two veins unite to form a compound vein (the Combination lode). By J. E. Spurr, 1911.

clearly ore deposition during rising temperature. In this case, however, there has been no upward movement of the associated igneous rock to account for it, and the explanation may be the gradual attendant upward intrusion, contemporaneous with the ore deposition, of one of the other bodies of similar rock, which are very abundant and very near by.

CHAPTER VI

The Near-Surface Telescoped Ore Deposits

This chapter deals with those ore deposits formed within a few thousand or even a few hundred feet of the surface, mainly in Tertiary surface volcanics. These sometimes represent all the metals of all the plutonic ore-sequence zones; I infer that they have been formed at the same critical temperatures as the latter, but that the fall in temperature has been so rapid that the superposition of one upon another has resulted in "telescoping," so that the whole vertical range is sometimes compressed within a single shallow-formed set of veins.

BEFORE REFERRING to the cases of reversed sequence in Chapter V, I had discussed the relation of certain igneous-rock textures to the corresponding major zones of ore deposition with which they are most intimately associated; and I thus described the characteristic texture association for the principal zones, from molybdenum (and tin and tungsten) to silver. These zones, as described, mainly and typically occur in connection with intrusive rocks. While the tungsten and gold-quartz veins (zones A and B) have plainly formed at a depth of many thousands of feet, and the principal silver zone (zone G) was formed far above, yet this last-named zone has in some cases (as at Aspen and Georgetown) plainly formed at no very shallow depth. At Georgetown, the total erosion since the intrusion of the porphyries is estimated at a minimum of 4,500 feet and a maximum of 5,250 feet, or more.[1] This, however, is measured to the bottom of the deep mountain valleys, while the ore deposits occur at all elevations, from high up in the hills to below the valleys, so that possibly a minimum of 3,000 feet may be assumed as having been removed from the uppermost orebodies exposed: and it

[1] *Professional Paper* 63, U. S. Geol. Surv., p. 145.

was estimated that the vertical range of this zone of ore deposition was several thousand feet, "probably 5,000 feet."[2] At Aspen, a calculation of the relation of erosion to progressive faulting and ore deposition indicated that the various stages of ore deposition took place at a depth of between 5,000 and 10,000 feet; and the vertical range of the ore zone is upward of 3,500 feet. The rough estimates in these two districts, arrived at from quite independent data, seem to give some approximate idea of the actual depth of this type of mineralization in this particular region.

Above this depth, however, as is well recognized by geologists, abundant ore deposits have been formed—that is to say, in the uppermost 3,000 feet and even 1,000 feet of the earth's crust. They represent the important type of deposits associated with the mainly middle Tertiary volcanics (extrusive and intrusive lavas) of western North America, just as the moderately deep-seated orderly sequences above described are mainly characteristic of the late Cretaceous early Tertiary monzonitic intrusive magmas, in the same broad province. On account of the much younger age of these ore deposits in the Tertiary rocks, erosion has not had time to strip off from the rocks the 5,000 to 15,000 feet estimated at Aspen, the approximately 5,000 to 11,000 feet estimated at Georgetown and Idaho Springs, or the considerable column at Matehuala (where a minimum of about 7,000 feet and almost certainly thousands of feet more—probably in all at least twice 7,000 feet—have been stripped off from the principal copper zone).

In contrast to these, consider Tonopah, in Nevada, a deposit of the Tertiary type, where I have estimated that the main ore deposition took place at a less depth than 2,000 feet,[3] or the neighboring camp of Goldfield, where the sur-

[2] *Op. cit.*, p. 147. According to Bastin and Hill, the depth of the ores at the time of deposition may have been somewhat greater, some miles from Georgetown—in the Central City-Idaho Springs region, 7,000 to 11,000 feet. See p. 884, Chapter XX.

[3] *Econ. Geol.*, Vol. X, No. 8, Dec., 1915, p. 761.

face at the time of ore deposition is held by Ransome to have been only a few hundred feet above the present surface; or the camp of De Lamar, in Idaho, where Lindgren estimated the ore deposits to have formed at a depth of under a thousand feet. These ore deposits also have a shorter average vertical range, according to my observation, than those characteristic of the association with intrusive rocks at considerable depths. In all cases they may be bottomed by mining operations, and hence are relatively short-lived—all the more so because frequently their relative richness is so great that mining is feverishly prosecuted. Deposits of this type, depending upon the plane at which they have been cut by the present erosion surface, may, in my experience, go down several hundred, 1,000, or 2,000 feet, but probably not more than an occasional maximum of 3,000 feet: and in this they differ from the characteristic frequently well-differentiated ore zones at greater depth, where, as has been seen, the vertical range of the galena-zone orebodies may be upward of 3,000 feet—in fact, 5,000 feet or considerably more; and where, in the deep gold-quartz zone, as in California, a vertical range of considerably over a mile is indicated. And, similarly, a considerable vertical range of ore deposition is indicated for the deep copper deposits, which lie metallographically between the lead and zinc zones and the gold-quartz zone.

Mineralogically, these Tertiary veins are complex, but they are famous and valuable for their rich and highly concentrated deposits of silver and gold. The silver is characteristically in the form of rich sulphides, sulphantimonides and sulpharsenides, such as argentite, stephanite, pyrargyrite, polybasite, etc. Since the quartz gangue of such rich silver-bearing veins is abundant, the type strongly resembles the silver ores formed in greater depth, and described previously as typically belonging above the chief galena zone, in the orderly process of deposition attendant upon the cooling and crystallization of intrusive rocks; and, indeed, I believe it really is the same zone. But gold also

occurs in these veins, associated with the silver sulphides, or occurs as tellurides or as free gold. A highly variable ratio between gold and silver is characteristic of these deposits, some containing almost entirely silver, and some almost entirely gold; and others contain gold and silver in almost every ratio. In this, therefore, these deposits differ decidedly from the deeper silver-quartz veins, and, indeed, from most of the typical clean-cut vein types characteristic of the crustal depths. But this is not all; for at Goldfield, for example, large portions of the ore, particularly in depth, not only ran low in gold, but ran up to an average of 8 per cent or so in copper, so that it became a copper ore, and concentrates were shipped to the smelter for treatment. Also, these ores may contain considerable galena and blende, as in the case of the Comstock, where those ores which were lower grade as regards silver and gold became "base," or relatively high in lead and zinc. But that is not all, or, as one might say, "not the worst of it," in view of our orderly succession of metallization, as worked out for deep deposits, and sketched above. At Tonopah, for example, we have veins of tungsten ore (hübnerite and scheelite) associated with the rich silver ores and formed at about the same depth and epoch, although in a separate sub-epoch. Now, nothing is better established than that the natural home and deposition horizon of tungsten ore is deeply buried, close to the granitic magma, with which it evidently is intimately associated. The commonest metallic associate of tungsten is tin, which probably belongs to a still slightly deeper zone,[4]

[4] Since writing the above, in 1918, I note the confirmatory opinion of William R. Jones, as set forth in a paper in March, 1920 ("Tin and Tungsten Deposits: The Economic Significance of Their Relative Temperatures of Formation": Bulletin 186, Institute of Mining and Metallurgy, March, 1920), to the effect that tungsten is deposited at a lower temperature than tin, although frequently both occur together in the common zone—that is, where the bottom of the tungsten zone and the top of the tin zone overlap. He bases his belief largely upon the mineral associates of each, finding pegmatite and high-temperature minerals like feldspar, topaz, tourmaline, and the like more abundant in tin deposits than in those of tungsten; while tungsten deposits are more apt to occur in plain quartz

and although we have no tin at Tonopah, it has been found in Lander County,[5] Nevada, and in Mexico, in both cases in rhyolites, apparently of Tertiary age, and of such texture as to indicate cooling very close to the surface. Specimens I have seen in Durango (Mexico) are associated with topaz, just as is frequently true of the tin which occurs in pegmatitic veins in granites.

In fact, on the basis of our analytical studies of ore deposits associated with intrusive rocks, which have resulted in the conclusion that the different metals were deposited normally one above the other, and successively, with diminishing temperature, and, therefore, that each metal had its characteristic temperature of deposition or freezing, out of its magma solution, we should conclude that in these shallow deposits the whole gamut of critical metallization temperatures has been rapidly run, and, as we shall find, not necessarily in the normal order of declining temperature, but

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veins (those of pegmatitic origin); and also from the fact that tungsten veins are wont to occur further away, broadly speaking, from contacts with the parent granite than tin veins. In lower Burma, Siam, Malaya, and the Dutch East Indies, also, he finds indications that tungsten deposits occur at higher elevation than tin veins in the same districts. Mr. Jones quotes from Dr. Malcolm Maclaren (*Mining Magazine,* May, 1917, p. 249) as to the sequence in the East Pool mine, in Cornwall. These are highly interesting observations. Dr. Maclaren finds that the downward succession is roughly as follows: copper ores from the surface to 840 feet, tungsten from 840 to 1,200 feet, and tin from 840 to 2,040 feet, and possibly 2,700 feet, and says: "It is impossible to ascribe this vertical succession of minerals to any other cause than to decreasing temperature of metalliferous solutions with approach to the surface." Mr. Jones further remarks that tin (cassiterite) is being worked at Dolcoath, Cornwall, below 3,000 feet from the surface; and that tungsten (wolframite) has been mined down to the 1,800-foot level. In Cornwall, not only are there successive zones characterized, from the bottom up, by tin, tungsten, and copper, but still higher up, and further away from the granite, are zinc and lead minerals.

A curious thing about these tin and tungsten veins is the absence or scarcity of gold-bearing quartz. At Leadville, Colorado, however, gold-bearing quartz veins are reported to contain wolframite and scheelite. Molybdenite also rarely occurs with gold in quartz veins, but frequently with tungsten and tin. I will take up this problem in a later chapter.

[5] A. Knopf: Bulletin 640, U. S. Geol. Surv., 1916, pp. 125–138.

sometimes in reversed sequence, or up and down; and we should further conclude that the fluctuating temperatures of ore deposition in these superficial extrusive and intrusive lavas was as high at times as those of the plutonic stocks and domes of granite rock. We should conclude that these maximum temperatures reached in the surface lavas are higher than those at which the intrusive rocks—the porphyries—cool at medium depths, for these are not attended by the deep metallization zones. All this coincides, moreover, with the evidence that while the temperature of fluid granite and pegmatite magma is, say, between 550 and 800° C. (see p. 80), all temperature observations on rhyolitic lava at the surface, and the microscopic study of the rhyolites, indicate a magma temperature as high or higher (possibly around 1,000° C or more). It has been determined by Wright and Larsen that the phase of quartz which is common to granitic pegmatites must have crystallized below 575° C. In a temperature range below this point, therefore—and not such a very wide range, so far as can be estimated—the various principal zones, from tin and tungsten to silver, are precipitated in depth.

The ore deposits of the Tertiary shallow zone, which we are discussing, are associated exclusively with siliceous-alkaline, or intermediate volcanic rocks—trachyte, rhyolite, andesite—and not with basaltic rocks. These lavas, therefore, represent the superficial forms of the same magmas as are mainly associated with ore deposits in depth, in the Cordilleran region under discussion—syenites, granites, monzonites, granodiorites.

The evidence seems to be that where such a siliceous-alkaline or intermediate magma intrusion does not reach the surface, its slow cooling and crystallization create a succession of isothermic curves above and around the focus of heat, and that these curves determine the successive zones of metal deposition, one above the other, the uppermost being often still far below the surface; but where a breach in the crust is made, the magma passes rapidly up through the

conduit, and arrives at the zone immediately under the surface, or at the surface, with no loss of temperature, the heat generated by movement perhaps compensating or more than compensating for that lost by conduction into the cooler rocks through which it passes. The cooling and crystallization in this case take place entirely in the portion of the crust immediately at and beneath the surface; and apparently ore magmas are sometimes associated, similar to those assembled together when differentiation takes place in depth. But while the deep intrusion representing a heat focus has room to spread out its successive zones of metal precipitation above it for—in some cases—apparently a vertical range of several miles, in the case of the magma at and near the surface all these temperature zones must become very closely spaced or absolutely superimposed, so rapid will be the succession of isogeotherms between the normally lowest zone of precipitation (highest-temperature zone) and the surface.

At the surface we get only occasional slight precipitations of the metals, such as have been noted in fissures in volcanoes—for example, of tin, tungsten, arsenic, antimony, tellurium, cobalt, zinc, lead, and bismuth. Evidently, under these conditions, for some reason, no important ore deposit is possible: but at a certain, often relatively slight, depth, the ore magmas crystallize. Like the ore magmas which consolidate at great depths, these shallow ore magmas are sometimes apparently highly concentrated, and may play the rôle of an intrusive (as in the case at Tonopah, already mentioned), due to their potent telluric pressure. In other cases the shallow metal magmas are probably diluted in various degrees by water and gaseous components, and act mainly to form ore deposits of replacement, in which respect they also certainly correspond with the variation of the deep ore magmas.

To illustrate the intense and fluctuating conditions of this superficial zone of igneous intrusion and extrusion, I will sketch briefly the condition at Tonopah, a very typical

example. Here the complexities of magma migration at the roots of volcanoes is well exhibited.[6]

The oldest rock at Tonopah is a trachyte flow, of which the lower portion is finely flow-banded and glassy. Stresses subsequent to the trachyte extrusion produced horizontal fissuring near the zone of transition between the main body of trachyte and its glassy lower portion, and along here an andesite intrusion penetrated. After renewed fissuring along the same zone, a glassy trachy-alaskitic intrusion, very full of inclusions, took place, mainly following along immediately above the andesite. Subsequent movement along the same plane of weakness again reopened it, and a second trachy-alaskitic intrusive sheet or sill shoved itself in, and principally took up a position immediately above the last-named intrusive sheet. Later there came a copious surface flow of andesite, and still later a series of rhyolitic and alaskitic flows and intrusions.

The principal veins were formed after the trachyte eruption, and before any of the succeeding eruptions. They are quartz veins carrying silver and gold, and were relatively very rich. A second important set of veins were formed after the second trachy-alaskitic intrusion and before the succeeding andesite flow; and this second set has been differentiated, by my investigations, into four successive groups or periods: *a,* Large typically barren quartz veins; *b,* tungsten-bearing veins; *c,* veins of quartz and adularia, typically barren; *d,* productive quartz veins carrying silver and gold, and very similar to those of the first set following the trachyte. A third set of veins was formed after the last rhyolite-alaskite flows and intrusions. They are quartz veins carrying occasional lead, zinc, and copper sulphides, but are not ores of gold or silver.[7]

All these veins occur at very near the same horizon in the mines, and careful consideration of the data indicates that

[6] *Econ. Geol.,* Vol. X, No. 8, Dec., 1915, p. 713.

[7] Veins in rhyolitic rocks of this period at Goldfield and Divide are rich in gold or silver.

they formed at practically the same depth from the surface —namely, that the difference did not amount to more than a few hundred feet. Depth or pressure, therefore, had nothing to do with the differences of these various types; yet we perceive, if we are trying to identify the typical zones of the deep-seated deposits, the tungsten, copper, lead, zinc, and silver zones—in fact, practically the whole sequence from the typically most deep-seated, when connected with a plutonic intrusion, to the uppermost which I have recognized and discussed above. Since some of the most notable variations followed swiftly after a single magmatic migration—that is, after the second trachy-alaskitic sheet intrusions, when veins carrying only tungsten as ore were soon followed by rich silver-gold veins—there is little doubt that temperature was the controlling factor; and, therefore, that in this complex intrusion history the temperatures have fluctuated up and down the whole range which determines the deposition of the more orderly and slow-forming ore zones associated with "sealed" intrusions: meaning by the term "sealed" those intrusions which do not reach the surface or near it, and so do not find quick relief for their pent-up heat.

In Tonopah the quantities of metals representing the tungsten, copper, zinc, and lead zones are relatively small, and this is taken to indicate that these critical temperatures were only briefly sustained (Fig. 60). The abundant deposition was of silver-gold ore in quartz, so that the temperature-pressure conditions for this type seem to have been normal. We are tempted to identify this type with the rich silver ores which appear to occupy the zone above the lead zone, in the ore sequence connected with intrusive rocks, but there is the difference in the gold contained, and that this gold is almost as characteristic of this type of superficial deposits as is silver.

From all evidence, it is likely that this gold represents a separate low-temperature zone, normally overlying the rich silver zone; and that this gold zone is distinct from the

higher-temperature zones characteristic of the deep-seated sequence, where two other distinct zones of gold deposition have been noted: the first below the copper zone—the gold-quartz zone; and the second above the copper zone—in the pyrite-arsenopyrite zone. Silver, also, in these deep-seated deposits, shows two distinct recurrences of deposit—the

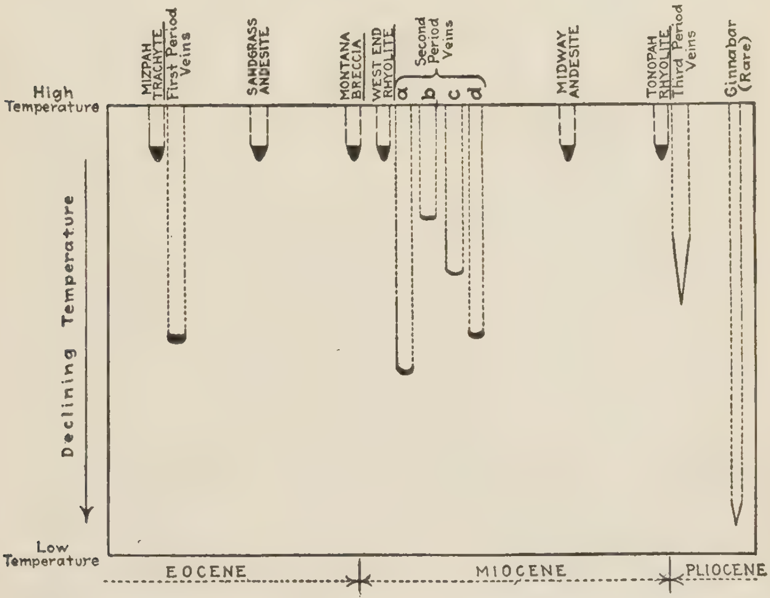

Fig. 60.—Tonopah, Nevada. Diagram to show Tertiary volcanic intrusions and also Tertiary vein injections, and to indicate relative temperatures of consolidation of veins.

first below the lead-zinc zone, in the pyrite-arsenopyrite zone, and the second above the lead-zinc zone.

In these deep-seated deposits, therefore, the lower silver zone corresponds with the upper gold zone, but the principle of recurrence is established for each: a principle which does not seem to apply to tin, tungsten, copper, zinc, and lead, all of which seem, as above outlined, to have a single definite *major* zone of deposition, determined by a definite temperature.

In such a composite or telescoped ore deposit as that at Tonopah, the gold content of all three temperature zones may be partly represented. The associated galena, blende, and chalcopyrite which is found with these rich silver-gold ores (all three minerals occur at Tonopah and in the Comstock lode, and, as before stated, chalcopyrite is locally abundant at Goldfield) further supports the idea of a "pooling" of the gold-silver magma segregations, since apparently a certain representation of all the major zones associated with the deep-seated gold and silver zones (the copper, lead, and zinc zones) is included.

Another possibly significant feature of these Tertiary rich silver-gold-quartz deposits is the frequent abundant occurrence of the rhombic form of orthoclase (adularia) as a gangue mineral, together with quartz. This mineral is possibly more characteristic of these shallow-formed Tertiary deposits than of any other; although I have found it in small quantity in connection with the copper zone at Matehuala[8], and it has been found in connection with gold-quartz veins of the deeper zone, as in California; also in connection with the copper deposits of Michigan, in the copper deposits of New Jersey, and as an important contact-metamorphic mineral in Norway, in connection with ores of copper, zinc, and molybdenum.[9] Lindgren believes that these Tertiary deposits, characterized by adularia as a gangue, do not form at temperatures above 150° C[10]; and he classifies these accordingly as low-temperature deposits. Personally, I am unable to see any reason for this conclusion, except by inference from the shallow depth at which they were formed: but, as above indicated, the actual evidence does not seem to me to indicate low temperature.

The metallic minerals, of course, in view of their wide range of deposition in the deep-seated deposits, do not point in this direction; and of the gangues, quartz, adularia and

[8] *Econ. Geol.*, Vol. VII, No. 5, Aug., 1912.
[9] LINDGREN: "Ore Deposits," pp. 476, 716.
[10] *Op. cit.*, p. 78.

calcite are the principal ones. The quartz is characteristically finer grained than that of the quartz veins in depth, but this probably indicates rapidity of crystallization (like the corresponding fine texture of the associated volcanic rocks) and not initial temperature. Calcite, too, is a gangue mineral which is found through the whole range of ore deposition in depth. As to adularia, its occurrences in connection with the deeper veins, some of which I have noted, shows that it may form at considerable depth: indeed, I believe that possibly its principal occurrence in depth is in connection with "contact-metamorphic" deposits, and in the druses of granites: that it is as characteristic of such conditions as of the upper zones of ore deposition, such as the lead, zinc, silver zones; and, therefore, is not a low-temperature mineral.

At Tonopah, the principal quartz-adularia veins are barren, and occur in a vein sequence immediately following the second trachy-alaskitic intrusion, after the tungsten veins, and before the ore-bearing silver-gold veins, which have as gangue principally rhodochrosite and quartz. If this is a regular sequence, it indicates in this case a moderately high temperature for the formation of the adularia, between that of the deposition of tungsten ores and that of the silver-gold ores.[11]

[11] An instance of the artificial production of adularia of which I have note was by Sarasin and Friedel (*Bulletin Soc. Française de Min.*, Vol. IV, 1881, pp. 171-175; *Chemisches Centralblatt*, 1892, Vol. I, p. 865), who obtained, by heating a mixture of potassium carbonate, alumina, silica, and water, tiny quartz crystals and adularia. The temperature of the experiment was 500° C. Calcite in rhombohedral crystals was obtained at the same temperature. Beck-Berg ("Abriss der Lehre von den Erzlagerstätten," 1922, p. 112) cite the experiments of Königsberger showing that the feldspars can only be formed at or above the critical temperature of water (orthoclase down to 340°). In cooler solutions mainly hydrous zeolite-silicates formed. Morey and Niggli (*Jour. Amer. Chem. Soc.*, Vol. XXXV, No. 9, p. 1086) summarize various experiments in the formation of orthoclase and other feldspars. Besides the experiments above noted, Friedel and Sarasin obtained the crystallization of orthoclase and albite at 400° C. K. von Chroustschoff obtained the formation of adular feldspar (adularia) and quartz at 300° C; and C. and G. Friedel noted that at 500° C. orthoclase

Finally, I wish to refer to that most superficial type of magmatic deposition of metallic minerals which has been observed around the fumaroles of volcanoes. On the crater of Vulcano—from which all other volcanoes take their name—fumaroles or jets of gases, including water gas, escaping at the surface, have deposited (besides the non-metallic salts of soda, potash, ammonium, lithium, and boron) compounds of tin, bismuth, cobalt, copper, zinc, and lead.[12] This, it will be observed, gives nearly the whole range of metallic deposits formed in veins under plutonic conditions. Are these metallic depositions (which, though scanty, and commercially not ores, are deeply significant) low-temperature deposits? The surface temperature of the lava pool at Kilauea (Hawaii) is about 1,000° C. The temperature of hot water-gas, emerging from the crater of Taal, in the Philippines, has been determined as over 400° C; and other fumaroles have been found to be considerably hotter; while others, of course, are very much cooler. Evidently, the

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was formed from mica. Emil Baur observed the crystallization of quartz, orthoclase, oligoclase, albite, and muscovite at 350 to 520° C. Doelter obtained orthoclase at 400°. In view of these and other experiments, Morey and Niggli observe: "From the experiments of Lenberg, Doelter, and Thugutt, it is evident that zeolites or zeolite-like substances . . . are easily prepared at temperatures ranging from 100 to 200°. . . . The number of hydrated compounds naturally diminishes with increasing temperature, but this circumstance has no connection with the critical point of water. As a matter of fact, many hydrated silicates have been obtained under conditions which point to their formation from solutions at temperatures above 400°, and therefore presumably from fluid (not liquid) solutions. It appears that the parageneses—the nature of the minerals obtained—are but little altered by change of pressure and temperature within the approximate limits 300 and 500°. . . . In this region are found the minerals most commonly obtained from these experiments—quartz, albite, orthoclase, analcite—substances that have been so often prepared that there can be no doubt that they may be formed in nature under similar conditions. . . . It has been demonstrated that feldspars can be formed in the presence of aqueous solutions at temperatures ranging from 300 to 500°."

[12] Other metallic minerals which have been found around fumaroles include arsenic in the form of sulphide (realgar), mercury (cinnabar), antimony, and tellurium.

temperatures at the surface, where the fumaroles deposit metallic minerals, may be as hot, so far as our criteria go, as the temperatures at which the corresponding plutonic deposition of the same minerals takes place. And if this is the case, those ore deposits which form near but below the surface, in recently cooling lavas, may well also be deposited at temperatures as elevated as those formed at considerable depths.

Metallic deposits have not been noted on all volcanoes studied: they have not been described, for example, from the basaltic volcanoes of Hawaii. The lava of Vulcano is a siliceous rhyolite; and it may be that such metallic precipitates will be found to be more characteristic of siliceous lavas. It may further be found that they will not occur in connection with all craters carrying siliceous lava; and, following the genesis reasoned out for ore deposits at whatever depth, that they indicate the presence below of the highly specialized and independent magma segregations which are responsible for the chief ore deposits: magma segregations which, originating at a considerable depth, on occasion follow the lava upward.

We must now, perforce, since we have apparently discerned a plutonic or deep-seated sequence of vein deposition and a corresponding superficial sequence, admit the existence of a corresponding intermediate sequence.

The plutonic sequence has been interpreted and defined as having the base of its column at the zone of magma differentiation, where a magma (generally in the form of a boss, stock, or mass) upsurging from the depths below, where conditions apparently have long held it relatively stable, begins, apparently partly by virtue of incipient crystallization processes, to segregate or differentiate, with the resultant grouping together, under favorable circumstances, of the metals into a specialized ore magma. This ore magma, ascending through the overlying rocks, which have a very gradual decrease in temperature upward, on account of the depth at which they lie, deposits the metals in regular suc-

cessive zones, as tin or tungsten, copper, zinc, lead, and silver; or gold, copper, zinc, lead, and silver (See Chapter XIII); and the typical combined maximum vertical extent of all these zones (which may roughly be estimated from our fragmental data as having a maximum vertical range of at least a mile each) can hardly, as I view it, be less than five miles. And yet the uppermost ore zone does not necessarily reach very near the surface. The temperature of the plutonic hearth which so frequently forms the base of such a sequence has been shown to be probably moderate; hence the fall of temperature between it and the surface will be, in the simplest instance, gradual and regular.

Contrasted to this sequence is that connected with surface volcanics and their attendant metalliferous deposits, where the magmas, instead of crystallizing in depth, ascend through the crust and reach the surface, or close to it, at a temperature as hot as or hotter than when they left the depths. These magmas cool suddenly at or near the surface, with the resulting characteristic dense or even glassy texture, and a total absence of internal differentiation phenomena. On account of the elevated temperature all along the route upward to the surface, the specialized ore magmas likewise reach very near the surface before they are crystallized or are precipitated, and then their total metallic contents are thrown down, not in an orderly and vertically extensive series of zones, but all within a probable maximum of a few thousand feet of the surface, so that the different metallic ingredients tend to be more closely associated, or even mingled, and the normal ore zones are "telescoped."

Suppose, now, that the temperature and intrusion conditions are intermediate between the two extremes mentioned: that the rock magmas do not slowly crystallize in depth, but ascend upward from the differentiation zone till they are arrested, by the falling temperature, at intermediate depths. They then crystallize, as is well known, with texture and structure intermediate between those of the

granular rocks in depth and the lavas at or very near the surface—usually with a prominent porphyritic structure and fine granular groundmass. The ore magmas which are sometimes associated with such upward invasions, and which may follow them up, will also tend to be first arrested, crystallized, or precipitated at intermediate depths; and the resulting ore deposits, in the matter of vertical range, clear separation of zones, or overlapping or combination of zones, will be intermediate between the two typical extremes above cited, and in all degrees. Since the outlying (up-lying) situation of these intrusive salients of rock magma exposes them to relatively quick cooling, the temperatures will normally drop with relative rapidity during the ore deposition, with the result that distinct zones or, to put it more directly, distinct types of metal deposits, are superimposed one upon the other. Compound veins,[13] caused by the splitting open of an earlier vein, and a filling of the new fissure with another type of ore deposit, will be especially characteristic of these intermediate conditions, or the later deposits may occur as distinct veins, or as later ore-shoots in the earlier veins. In these intermediate depths, moreover, the ore-magma deposition may be synchronous with another upward invasive surge of the rock magma, slowly ascending in its wake, and the rising temperature will cause an inversion of that normal order of deposition of the different metals which takes place with falling temperature. Such is the case, for example, at Aspen, in Colorado, and Tiro General, in Mexico, as already described. Or a sudden brief wave of heat, due to a surge and subsidence of the invasive magma below, may be recorded in the ore deposits above, which may show, first, the normal order of sequence, and toward the end the inverted order; or the inverted order followed by the natural order. Under these intermediate

[13] I use the term *compound veins* in a new and very obviously fitting sense. The term *composite* veins has long been used by European geologists as a physical term, to indicate a lode which comprises a number of smaller veins. I have no great need of a special term to convey this condition. My definition is a genetic-physical one.

conditions, as well as under superficial conditions, complex ores will often be formed, containing the different metals so closely associated as sometimes to make their genetic analysis, and indeed their separation for commercial purposes, a more or less difficult problem.

When, however, a certain range of temperature is steadily sustained for a long time, then not only the ore deposits of the deep-seated or plutonic group, but those of the intermediate depths, will tend to be clean cut and individual, and in more or less separate zones: moreover, the amount of mineralization in each zone will tend to be great. Zones of mineralization like those of the gold-quartz veins of California, or the copper deposits of Butte, indicate such steady and favorable conditions of temperature.

CHAPTER VII

The Aplitic, Pegmatitic, and Superpegmatitic Rock and Ore Magmas

This chapter explains the difference between aplites and pegmatites as indicating a differentiation of magmas of the same general composition into relatively dry and relatively aqueous divisions, from which respectively aplites and pegmatites consolidate. Not only is this true for rock magmas, but probably for ore magmas also. At Santa Eulalia, in Mexico, of two types of ores, one is argued to have been derived from a dry or aplitic ore magma, one from an aqueous or pegmatitic ore magma. The aplitic ore magma does not dissolve or replace limestone; but the pegmatitic magma forms replacement bodies in limestone. The extreme type of pegmatitic magma is termed the superpegmatitic magma. It is believed that superpegmatitic rock magmas also replace and modify earlier magma crystallizations. At Velardeña, the unbroken sequence of crystallization reaches from the earliest stages of rock minerals through the stage commonly called metamorphism to the metalliferous veins and finally to the barren veins.

AT SILVER PEAK the alaskite is both aplitic and pegmatitic in texture (alaskite aplite and alaskite pegmatite); and transitions between the two occur. It was noted that the alaskite pegmatite was the variety which was chiefly found transitional into the gold-quartz veins,[1] and primary free gold was found in this pegmatite.

It was also noted[2] that in the ore-bearing district the pegmatitic alaskite was especially abundant, as compared with the aplitic, or even medium-textured alaskite, while in neighboring portions of the same range, where no ore deposits of importance had been found, the denser, fine-grained, aplitic textures of alaskite predominated.

[1] *Professional Paper* 55, U. S. Geol. Surv., p. 99.

[2] *Op. cit.*, p. 24.

The significance of the varying texture of these alaskites, however, was not fully recognized until after I had made studies of alaskite aplites and pegmatites at Helvetia, Arizona, where there is a series of siliceous igneous intrusions of probably late Paleozoic early Mesozoic age into Paleozoic sedimentaries, with attendant metallic deposition (chiefly copper, some lead, molybdenum, etc., and, at an earlier period, very subordinate typical gold-quartz veins); and where the relations are more clearly demarked.

The sequence of intrusions at Helvetia appears to have been:

1. Biotite granite, with an earlier probable pyroxene granite phase (magmatically altered to biotite granite) and a later alaskitic phase. Very abundant.

   1-a. As after products, pegmatite and pegmatitic quartz veins, sometimes auriferous; decidedly subordinate quantitatively.

2. Alaskite-granite porphyry. An independent intrusive, distinctly more siliceous and finer grained than (1). Large intrusive masses and dikes.

   2-a. Subsequent diorite and quartz monzonite dikes, very subordinate quantitatively.

3. Alaskite aplite; important and large irregular dikes in granite; distinctly more siliceous and finer grained than (2).

   3-a. Contemporaneous or slightly subsequent pegmatite and pegmatite quartz veins; extremely subordinate quantitatively.

4. Quartz aplite, or arizonite. Important dikes and masses in granite. Of same grain as (3) but more siliceous.

   4-a. Subsequent quartz veins, metalliferous; carrying copper, with small amounts of galena, blende, and molybdenite.

The quartz aplite, or arizonite (No. 4), it may be explained, is a peculiar highly siliceous aplitic dike rock which I have first described from this locality, and named; it is an alaskite aplite with the feldspar reduced so as to form an accessory constituent, so that quartz is by far the most

important constituent; thus, the rock belongs to a more siliceous group than do the alaskites. On account of the even aplitic grain and texture, the rock resembles very closely a quartzite (Fig. 61). Besides feldspar, the usual granitic accessories (zircon, muscovite, garnet, etc.) occur.

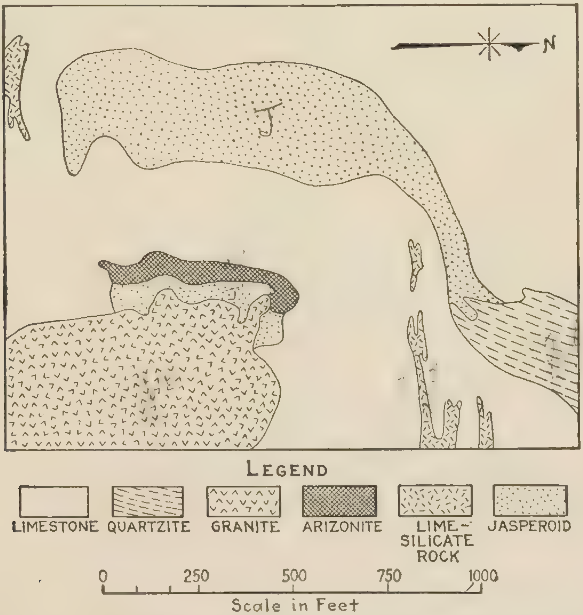


FIG. 61.—A study in siliceous rocks. Part of a plane-table survey in the Helvetia district, Arizona. Granite is intrusive into folded Paleozoic limestones with some quartzites. A later intrusion is arizonite (practically an "igneous" quartz intrusive). Jasperoid has originated by replacement of limestone by silica. The three quartz rocks—sedimentary, igneous, and metasomatic ("metamorphic")—are chemically and physically very similar, and difficult to distinguish even under the microscope. Another metasomatic ("metamorphic") rock is the pale-colored lime-silicate rock, formed, like the jasperoid, by replacement of limestone by siliceous aqueous solutions, but at a higher temperature. By J. H. Farrell and L. B. Smith, under direction of J. E. Spurr.

The noted relationship of the types (1) and (2) above, of (2) and (3), and of (3) and (4) is in many places in the field clearly observable, through transition phases. It is plain that these represent successively ejected phases of a

granitic magma in process of differentiation. The evidently complementary diorite and quartz monzonite dikes are interesting but quantitatively unimportant. The general process illustrated (by the sequence 1, 2, 3, and 4) is the growing siliceousness of the magma by withdrawal of the ferromagnesian minerals and the calcic feldspars, the rock becoming more siliceous and more alkaline; and finally the withdrawal of a large part of the feldspar, leaving an essen-

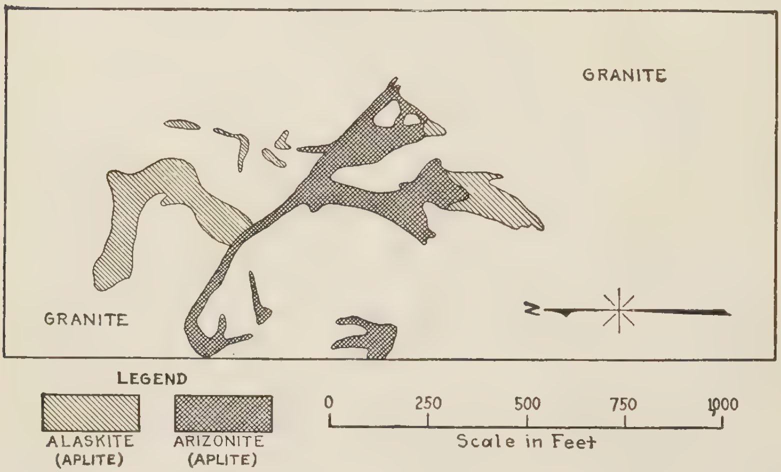


FIG. 62.—Arizonite and alaskite aplitic intrusions into granite; Helvetia, Arizona. Plane-table surveys by J. H. Farrell and L. B. Smith, under direction of J. E. Spurr. The arizonite is slightly later than the alaskite, which it cuts: nevertheless, it is also transitional into it, as shown by the segregation of alaskite in three places *at the tips* of the arizonite dikes.

tially quartz magma, which became intrusive into the earlier consolidated phases.

The fact that the quartz aplite or arizonite solidified with a homogeneous fine grain throughout, the grain and structure being identical with that of the somewhat earlier but closely related alaskite aplite, indicates that the two magmas (quartz and quartz-feldspar) had about the same viscosity, and cooled under the same conditions and at the same rate. (Fig. 62.) The quartz magma, which became arizonite (like the slightly earlier quartz-feldspar magma

which became alaskite aplite) was not attenuated and aqueous, even though residual. Crystallization set in simultaneously in numerous closely adjacent centers, so that the growing quartz crystals interlocked in a uniform quartzite-like mosaic; and the great viscosity is evidenced by the homogeneity of texture and composition. Gases or aqueous vapor, which would have increased the freedom of crystallization,[3] were probably present in no perceptibly larger degree than in the alaskite aplite.

A silica-saturated magma, in which crystallization was induced simultaneously throughout its mass, by cooling or relief of pressure, or both (resulting from its intrusion as dikes into already-solidified rocks), and was entirely finished in a relatively short time, is indicated.[4] No evidence was noted that the material residual from the solidification of the arizonite was quantitatively more important than that residual from the alaskite aplite or from the granite. The dikes seem to occupy the whole space into which they were intruded, though, indeed, in the case of this and the other intrusions, it is likely that the walls of dikes would accommodate themselves to the contraction of the cooling igneous rock, closing with relief of pressure.

It is significant that the alaskite aplite was attended or closely followed by typical small veindikes of pegmatite and pegmatitic quartz, the size of the crystals in which were many times (20 to 30 times) larger than those of the mother rock; and was also followed by the abundant later and independent arizonite intrusion, of composition similar to that of the pegmatite and quartz. This squarely defines *the practically contemporaneous existence of two magmas from which quartz- (orthoclase) rock of similar composition crystallized: the one magma highly fluid and probably attenuated through the presence of much water and gases; the other viscous, and containing relatively little of these mobile constituents.* The latter resembles in density the normal

[3] *cf.* J. P. Iddings, "Igneous Rocks," 1909, p. 188.

[4] *Op. cit.*, p. 161.

igneous magma; the former is a residual magma chiefly notable for its relative concentration of the mobility-favoring fluid "crystallizers" or "mineralizers." There are also, certainly, transition phases between these two magma types exemplified in other districts, but none were noted in this.

In many other districts, the residual quartz magma of the former (pegmatitic) type is the more abundant and important one.

The essential difference between an alaskite aplite and an alaskite pegmatite is here clearly emphasized; and indeed between pegmatites and aplites in general.[5]

The Silver Peak and Helvetia observations, taken together, indicate that the differentiation of certain rock magmas leads, on the one hand, through granites to alaskites of aplitic texture, and these to certain quartz veins (veindikes); and, on the other hand, that the differentiation leads through granites to alaskite pegmatites and these to pegmatitic quartz veins (veindikes). The latter (aqueous) residual magma is the parent of certain mineral deposits, the solutions residual from the pegmatite deposition yielding, by subsequent selective precipitation, certain metallic and non-metallic precipitates of commercial value.

[5] With regard to the problem of the relation of pegmatite to aplite, consider, further, the accompanying sketch (Fig. 63), which I made at the rapids of Wintering River, in Manitoba, in 1916. In this region a reddish granite cuts an older gray gneissic granite (see Chapter III). The younger reddish granite has pegmatite and aplite offshoots; and the figure shows, first a red pegmatite dike a foot wide, and second a red aplite dike of the same width, cutting and faulting the pegmatite. The pegmatite consists of quartz and feldspar, with a little biotite; the aplite, of quartz and feldspar only. Each has fairly uniform crystallization, the aplite more markedly so than the pegmatite. The average diameter of the crystals in the aplite is one-twentieth to one-thirtieth of an inch; in the pegmatite, one to one and one-half inches. Thus the grain of the pegmatite is 20 to 50 times coarser than that of the aplite; yet each occurs in dikes of the same width, from the same magma, and of the same general period—meaning the same cooling conditions. This demonstrates anew some fundamental difference between the pegmatite and the aplite magmas, which difference is not one of chemical composition; and which I think must be referred to great differences of fluidity or viscosity. Note that the aplite is *finer grained* than the normal red granite, the pegmatite *coarser grained.*

The siliceous metalliferous solutions which are among the residues from this phase of magmatic differentiation are not siliceous because of any chemical affinity between silica and the metals (a fact which I pointed out in the first paragraph of this book), but the two are associated only because both are residual.

To repeat, there is evidently a strong differentiation or segregation tendency, in the alaskite magma which is residual from the crystallization of granites, to separate into a relatively dry and a relatively aqueous product—the silica

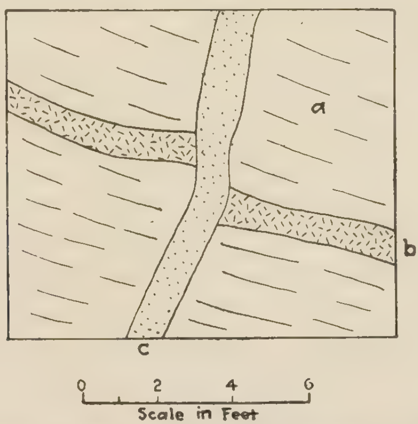


Fig. 63.—Illustration of essential difference between aplite and pegmatite magmas. a, Gneissic gray granite; b, red pegmatite; c, red aplite. See text. Sketch on Wintering River, Manitoba, J. E. Spurr, 1916.

more concentrated in the former, and the water and other mobile and dissolved constituents important in the latter. The first product crystallizes as alaskite aplites and rare arizonites, and the latter as pegmatites, frequently metalliferous, and as quartz veins, much more frequently so.

On investigation, we shall find that what has been shown to be true of the alaskite magma—its separation into a relatively dry magma and an aqueous magma, or an aplitic and pegmatitic magma—may well be true of certain other igneous magmas, and is also probably true to a greater or

less extent of ore magmas, and this repeatedly and in the various stages.

An interesting and unique example is found in the old and highly productive silver-lead mining camp of Santa Eulalia, near the city of Chihuahua, in Mexico. These mines have been worked for two hundred years, and have produced $300,000,000 to $500,000,000 worth of ore. My observations here were made in the course of several examinations, with a corps of assistants. The district is in the thick-bedded Cretaceous limestone which covers, as frequently above stated, nearly all this part of Mexico, and which is thousands of feet thick. The beds have been very slightly disturbed—broad undulations marked by dips of around 10° being the rule. There has been a later period of volcanic activity, with a succession of tuff beds, consisting of volcanic material of both andesitic and rhyolitic nature, and one rhyolitic flow, the whole being intercalated with beds of conglomerates. This whole series, which is several hundred feet thick, constitutes a "capping" over the limestone, on whose deeply eroded and irregular land surface it was deposited. A few small dikes of andesite and rhyolite cut both the capping and the limestone.

Such manifestations of igneous activity are what we have come to look for in any district of ore deposition; but in this case, the primary ore deposition was earlier than all of this igneous activity. Both capping and dikes are distinctly later than the ore, which was formed in the nearly horizontal limestone in large quantities. The orebodies have formed in sheets spreading out along some favored limestone stratum, or in chimneys, in part apparently due to the intersection of strong fissures, which have been traced and mapped in the limestone, and along which the mineralizing solutions seem to have ascended. (Fig. 170.) Many of the fissures are remarkably strong and continuous, and sets having different strikes are shown by geological criteria to have formed at the same period. The set along which the primary sulphide mineralization has formed runs nearly

north and south; and along such fissures important ore-bodies occur at intervals, or connectedly. Strong transverse fissures, running about N. 35° E., are distinctly post-mineral and barren, and are later than the capping.

There are two distinct types of ore occurring in different portions of the district. The prevalent type, where unaltered, is a galena-blende-silver ore, containing blende, argentiferous galena, pyrite, and pyrrhotite, all in considerable quantities. In depth there is a marked increase of pyrrhotite over pyrite, as compared with the upper levels.

The second type, only recently discovered at the time of my examination, in the Potosi mine, is unique in my experience, but clearly represents that pyrite zone which has been described in several instances above as belonging between the principal copper zone and the principal zinc-lead zone. In this ore, pyrite and pyrrhotite, containing considerable amounts of silver and a little gold, form the principal sulphides, and are associated with black radiating iron silicates which form abundant and clearly contemporary gangue materials. In some cases, the silver values in these pyritic ores run very high.

Judging from the association of silver and some gold with pyrite and pyrrhotite, these ores correspond to those at La Paz, at Matehuala; but the occurrence of silicates as gangue renders the situation unique. Examination of the silicates emphasizes the peculiarity of the occurrence; they were determined for me in thin section by Dr. F. W. Wright as fayalite (ferrous silicate) and ilvaite (iron-lime silicate).

My reports on this district were written and distributed (though not published) in 1911. In 1915, Mr. Basil Prescott, who had been geologist for mining companies at Santa Eulalia, published a study of the district, in which he corroborated most of my conclusions, and added a great deal more of investigation and careful geological observation. He confirmed independently the determination of fayalite and ilvaite (which I had not incorporated in my report, as the determination came a few weeks later than the com-

pletion of the report), and found also the rare mineral knebelite (silicate of iron, manganese, and magnesium) as one of the silicate gangue minerals.

Fayalite was here for the first time, I think, recognized as a gangue mineral with ores. It has been reported almost exclusively from igneous rocks. Ilvaite occurs apparently both as a metamorphic mineral in limestone, and in granites: in the latter association, it has been reported from a mine in Italy, accompanied by actinolite; and from the Cumberland, Rhode Island, iron district, associated with hornblende and magnetite; also from a magnetite mine in Shasta County, California, associated with garnet and hedenbergite, pyrite, and chalcopyrite.[6] Knebelite is reported from mines in Norway. The total list of minerals in this argentiferous pyrite ore at Santa Eulalia, as described by Prescott, includes also hedenbergite (iron pyroxene). The metallic minerals include arsenopyrite and magnetite, with some galena and chalcopyrite.

The two types of ores—(1) galena-blende, and (2) argentiferous and auriferous pyrite and pyrrhotite—are distinct orebodies in the same mine—the Potosi—and evidently distinct in origin. From analogy with the Dolores mine, in Matehuala, and other occurrences, I assumed that the galena-blende ores were probably later than the argentiferous pyrite ores; and this was determined quite definitely later by Prescott, who found that the ores of the former type invariably cut those of the latter type.

The consanguinity of these two distinct types of ores is, however, indicated by their having certain minerals in common, such as pyrrhotite, galena, blende, calcite, quartz, and fluorite; and the presence of these last three gangue minerals in the argentiferous pyritic ores, together with the lime silicates, indicates the critical temperature stage as at the lower end of the silicate scale of temperature. This is also indicated by the high iron content of the silicates. The one silicate found in common with the Matehuala ores is the

[6] Basil Prescott: *Econ. Geol.*, Vol. III, 1908, pp. 465-480.

iron-rich pyroxene, hedenbergite. At Matehuala, where the long sequence of "contact-metamorphic" minerals is so well shown, the iron-rich silicates were the latest of the silicates to form, showing at that stage the presence of much iron in the magma solutions, which, when the formation of lime silicates began, were negative or poor as to iron, then neutral, until the final highly ferruginous stage appeared. At Matehuala this development of iron-rich silicates (hedenbergite or lime-iron pyroxene, andradite or lime-iron garnet, and actinolite or lime-magnesia-iron silicate) immediately preceded and in part accompanied the deposition of chalcopyrite; and the successively succeeding stages of, first, arsenopyrite, and then argentiferous pyrite and pyrrhotite, were later than the last lime-silicate deposition, and contemporaneous with a quartz-fluorite gangue, and, therefore, are believed to have been deposited at a lower temperature than the lowest temperature (about 550°—see p. 263) at which lime silicates, instead of quartz, calcite, and iron pyrite, are formed. In other words, if we apply this temperature scale to the metallic sulphides contemporary with the gangue minerals, it would appear that the argentiferous pyrite and pyrrhotite at Santa Eulalia were formed at a higher temperature than the same sulphide deposits at Matehuala, and indeed at the same temperature as the copper sulphide deposits at Matehuala. Now, at Matehuala it appears that the argentiferous pyrite-pyrrhotite ores (La Paz type) were formed distinctly later than the copper pyrite ores at the same horizon; or, when contemporaneous, several thousand feet above the chief copper deposition, which was near to the intrusive monzonite. At Santa Eulalia, the inferred intrusive magma in depth, from which rose the ore solutions, has not been reached; and in proceeding downward toward it, by all analogies—as at Mapimi, not far from here, and elsewhere—more cupriferous sulphides should be found. The unusual puzzle as to the indicated different temperature of these similar ores as

shown by the associated gangues, at Matehuala and Santa Eulalia, therefore remains to be explained.

At Santa Eulalia, the difference in age between the argentiferous pyrite-pyrrhotite ores and the argentiferous galena-blende ores is indicated not only by the latter cutting the former, as above mentioned, but by their occupying and following, according to Prescott, fissures differing somewhat in trend and in age. The fissures along which the former ascended were N. S. to N. 10° E., while those of the latter were N. 10° W. to N. 30° W. Both these types of ore are now found in the same general horizon—that is, they are not found one vertically above the other, as they would be if deposited contemporaneously (for the silver-lead-zinc ores without lime silicates denote certainly a lower temperature than the pyrite-pyrrhotite ores); therefore, since the silver-lead-zinc deposits are later, they record a falling temperature over the general period of the two depositions. This is also indicated by the general mineral sequence in the silver-lead-zinc deposits, where, according to Prescott, pyrrhotite was the earliest mineral, followed by sphalerite and then galena. That the temperature, however, fell very slowly and was well sustained during the whole of these stages of sulphide deposition is shown by the enormous quantities of sulphides deposited, and by the great vertical extent of ore: the pyrite-pyrrhotite ore had been developed with a vertical range of at least 1,000 feet, and the lead-zinc-silver ore with a vertical range of at least 2,000 feet, in 1915. Both these facts—the slow cooling, and the copious ore-magma solutions—indicate that a large body of magma was below; and the still missing copper zone indicates igneous rock probably still some thousands of feet below the lowest workings.

The peculiarity of the silicate gangue minerals at Santa Eulalia—differing, as we have seen, as to species, from the corresponding iron-rich silicates at Matehuala—merits our attention: on examination, the chief difference seems to be the greater amount of iron and manganese and the less

amount of lime at Santa Eulalia—in other words, the limestone through which the mineralizing solution-magma passed had less effect on it. Of the silicates, knebelite and ilvaite have been reported from magnetite deposits, of which some at least are described as of "contact-metamorphic" origin: these deposits usually contain some chalcopyrite, and so seem to be related to the copper-bearing "contact-metamorphic" deposits. The presence of much fine magnetite in the Santa Eulalia ore links it genetically with this type. In many deposits described—as at Heroult, California, by Prescott[7]; at Cornwall, Pa., by Spencer[8]; at White Horse, Northwest Territory, by Stutzer,[9] and in the Boundary District, British Columbia[10]—chalcopyrite is stated to be later than magnetite: although at the Imperial mine, Utah, Butler finds magnetite in part later than the chalcopyrite.[11] Altogether, the evidence would favor a higher relative temperature for the Santa Eulalia pyrite-pyrrhotite ore than that assigned above for this argentiferous pyrite-pyrrhotite type of ore at Matehuala. But the limestone away from the orebodies and even in their walls is unaltered to silicates, and is not even "marmorized." *The indicated explanation is that the ore was intrusive, as a magma, with little or no excess water;* that this magma, segregated out at the usual temperature of the pyrite-arsenopyrite stage, and drawn off into separate bodies, had its temperature raised moderately by some igneous accident, and while in this condition ascended upward as a dike, and so crystallized. With this explanation in view, consider Prescott's description of the ore: In shape, form, and dimensions, the type shows considerable variations, but the economically important occurrence is a tabular, veinlike body 5 to 15 meters in width, standing vertical and developed downward 500 feet below the capping, with ultimate

[7] *Econ. Geol.*, Vol. III, 1908, pp. 465-480.

[8] Bulletin 430, U. S. Geol. Surv., 1910, pp. 247-249.

[9] *Zeitschift Prakt. Geol.*, Vol. XVII, 1919, pp. 116–120.

[10] O. E. Le Roy, *Memo.* 21, Canada Geol. Surv., 1912.

[11] *Professional Paper* 96, U. S. Geol. Surv.

limits in depth unknown. The walls are parallel, and show as little variation and irregularity over great distances as do the walls of the average vein. The ore is usually "frozen" to the limestone, but there is no intergrading of the ore with the wall rock, and in the economically important occurrences no noted development of silicate minerals in the limestone.

"The ore itself is usually banded vertically, parallel to the walls. . . . "

Would such a result be possible from any aqueous solution traversing flat-lying limestone beds vertically? The later ores of the galena-blende type at Santa Eulalia spread out irregularly and extensively into limestone, along favorable beds, in the familiar manner of replacement deposits (Fig. 169, Chapter XX); and it is difficult to conceive how any but a magma singularly lacking in aqueous fluidity and replacing power could have invaded fissures in the way that the pyrite-pyrrhotite ore has done. In other words, the magma must have been less aqueous than a pegmatitic magma, which, as I have elsewhere observed, usually loses its identity in limestone and forms lime silicates. This Potosi ore magma, as revealed by the gangue minerals, even in the fissures did not amalgamate with the limestone, as thin solutions would have done. The formation of abundant magnetite (iron oxide); of abundant fayalite (iron silicate) instead of hedenbergite or andradite (lime-iron silicates); of knebelite (ferrous manganese silicate), instead of manganiferous hedenbergite or manganhedenbergite (lime-manganese-iron silicate); of ilvaite (basic lime-iron silicate) instead of garnet (andradite) and pyroxene (hedenbergite), can only mean *a magma solution phenomenally poor in lime for even an ordinary igneous magma, in spite of the fact that it had traversed thousands of feet of limestone and crystallized within limestone walls.*

Fayalite contains 70.6 per cent of ferrous oxide, partly replaced by manganese, and no lime; knebelite from 36 to 54 per cent ferrous oxide, from 8 to 30 per cent manganese oxide, and no lime; and ilvaite, 55 per cent of iron oxides,

and only 14 per cent of lime; while andradite contains 33 per cent of lime and only 31 per cent of iron oxide, and hedenbergite 22 per cent of lime and only 29 per cent of iron oxide. The fact that some hedenbergite did crystallize with these lime-free or lime-poor silicates shows that temperature conditions were favorable for it, and that lack of lime prevented a more copious formation, and conditioned the unique and abundant formation of these rarer silicates. It is difficult to see, therefore, how we can avoid the conclusion that this ore was intrusive in a fluid but highly concentrated state, containing no more water or volatile constituents than does the ordinary basic igneous magma from which the basic dikes solidify, and that it crystallized after intrusion, as dikes do: that it was a veindike verging in nature toward a true dike. The failure of this iron-rich magma (the ore averages, according to my analyses, 24 to 27 per cent of iron and only 8 to 9 per cent of lime) to absorb lime from the wall rock is commended for reflection to those geologists who believe that igneous magmas have the power of enormous digestion of their wall rocks.

The amount of iron in the magma was far in excess, apparently, of the amount of sulphur necessary for the formation of pyrite and pyrrhotite. The dike is, therefore, seen to have analogies with magnetic iron ores of igneous origin, like that at Cumberland, Rhode Island, which consists of magnetite and ilmenite, where also ilvaite occurs as a gangue mineral and where the ore is an extreme variation of a peridotitic igneous rock. In this connection consider the close relation of the iron ores of direct igneous origin (magmatic segregation) with the so-called contact-metamorphic magnetite deposits, as illustrated by the Cumberland, Rhode Island, and Heroult, California, types, referred to above. If the residual magma has enough aqueous and volatile fluidity to penetrate, absorb, and replace limestone, the ore which results has been relegated to the latter class (of contact-metamorphic deposit); if not, to the former class (of basic magmatic segregations).

It, therefore, appears that conditions analogous to the aplite-pegmatite rock series, whereby at a certain stage of differentiation a dry and a highly aqueous division may form by the drawing off of the aqueous and volatile constituents, while otherwise the magma composition of the two portions is the same, may also come about at any stage of ore-magma differentiation. The Potosi ore veindike is, in this sense, an aplite type, while a similar pegmatite differentiate, with more water and volatile constituents, which would have replaced the limestone, would have formed pyrite-pyrrhotite-magnetite replacements of vast extent. With more sulphur in the magma, the aplitic ore-magma phase would form intrusive pyritic bodies, analogous to the Mandy, while the pegmatitic phase of the same would produce an ore like the Flin Flon (pp. 110, 122).

The argentiferous pyrite magma at Matehuala was somewhat aqueous, for it replaced the limestone in the Dolores mine, where a fissure vein of pyrite passed out of the monzonite into the limestone. But in the case of the Potosi, it seems that the corresponding pyrite magma may have become dewatered and reheated (possibly by approach to another intrusive neck of the parent magma), and ascended as a relatively dry melt, far into the limestone above.

At Matehuala, in the La Paz mine, the pyritic ores run from 400 to 1,600 grams in silver; and a vein (the San Miguel) in the near-by Dolores mine, which I sampled, averaged 591 grams. At the Potosi, 70,000 tons of the better-grade ore averaged by my sampling 804 grams silver, and 977,000 tons of poorer ore, 241 grams. The silver content, in both districts, is thus seen to be similar; and there is, moreover, a very little gold in each. The enormous quantity of the Potosi ore, which was only partly developed at the time of my visit, is indicated by the tonnage, approximately 1,000,000, already proved, and indicates a large igneous magma—a differentiation laboratory—in depth, as do the great quantities of the silver-lead-zinc ores which were somewhat subsequent.

I have called attention above to the differences between granitic aplites and pegmatites, as worked out by me at Helvetia (p. 313), as being essentially respectively dry and aqueous variations (differentiates) of the same granitic or alaskitic magma—the one drier than the normal, producing an abnormally fine and even texture; the other more aqueous than the normal, and producing abnormally coarse and uneven crystallization, leading to the segregation of various constituents into accumulations which often become economically important. On reflection and observation, I am inclined to still further extend this classification, and make it triple—the dry phase, the aqueous phase, and the aqueous-gaseous phase—which we may call, for convenience, the aplitic, the pegmatitic, and the superpegmatitic magmas.

I believe we may recognize such phases in the aplite-pegmatite series of granites and alaskites, the aqueous-gaseous, or superpegmatitic, phase being represented by those pegmatites which are rich in minerals containing volatile elements, like apatite, tourmaline, and mica. There will be transitions between all these phases, of course, and occasional extremes will be represented. Of the three phases, the aplitic phase behaves as a dry dike-rock would be expected to; the pegmatitic phase, as already noted, and as every field geologist knows, is more penetrant of intruded rocks; and the superpegmatitic phase is still more so. With limestone, the pegmatitic and superpegmatitic magmas combine to form lime silicates, and they tend to penetrate and to pegmatize less soluble rocks. Doubtless the most potent elements in accomplishing this are the gaseous elements; and in the extreme gaseous or superpegmatitic phase, we may believe that the penetrant power of this magma becomes very great.

It is known that the aplite-pegmatite differentiation phases characterize not only granites and alaskites but (to a less degree) basic rocks as well; and, therefore, we may look in these cases also for the three divisions so defined.

Let us consider, in view of the above, some phenomena which I have described at Velardeña, as regards the magmatic or metamorphic alteration of the igneous rocks. It will be recalled (Chapter V) that there are here three adjacent and magmatically related intrusions, variations of a dioritic or monzonitic magma: one intrusion being a dark dioritic or monzonitic rock high in ferromagnesian minerals; one, more siliceous, a quartz diorite or quartz monzonite; and one, still more siliceous, a siliceous quartz monzonite or granite. The field appearance of these is so distinct that they were, before miscroscopic study, provisionally called diabase, diorite, and monzonite respectively, although the numerous transitional types made it plain, even in the field, that all three are phases of a single magma.

Field and microscopic study shows that the sequence of crystallization is similar in all three phases. I quote from my summary:[12]

"The above data indicate an unbroken sequence of crystallization, beginning with the earliest minerals formed in the igneous magma, passing to the formation of the later rock minerals (at which period the earlier ones were somewhat altered), and thence, with no abrupt break, to minerals commonly recognized as the products of 'metamorphism' (from the fact that they take the place of earlier minerals), and so on to the commoner vein minerals, such as quartz and calcite. It also shows that as the process of crystallization went on, the new (residual) materials were more prone to attack, and to become quantitatively effective in replacing and altering the earlier minerals, indicating that the magma became more mobile and penetrant, which probably means, among other things, that the magma became much more aqueous. Moreover, the process of events seems to have been similar at the various intrusions.

"The earliest minerals deposited from the dioritic magma appear to have been (A) calcic feldspar (chiefly andesine-

[12] *Econ. Geol.*, Vol. III, p. 704.

oligoclase) and some hornblende. This was succeeded by (B) magnetite, biotite, and grass-green pyroxene, which partly replaced in unusual cases the feldspar and commonly entirely replaced the hornblende, and crystallized in unoccupied spaces in the rock fabric. This was succeeded (though with no sharp break, so that the crystallizations overlap) by (C) orthoclase, apatite, titanite, chlorite, quartz, pale-green pyroxene, and pyrite. This was succeeded by (D) garnet and pyroxene (usually colorless); and this by (E) quartz and calcite."

After a study of the ore deposition as well as the metamorphism and the structure of the igneous rock, I drew up the following table of the order of events of igneous crystallization, and subsequent "metamorphism":

A. Andesine-oligoclase and some hornblende.

B. Magnetite, biotite, and grass-green pyroxene.

C. Orthoclase, apatite, titanite, chlorite, quartz, pale-green pyroxene, pyrite, chlorite, fluorite, zircon.

D. Garnet and pale-green to colorless pyroxene.

E. Cupriferous pyrite, pyrite, quartz, and calcite.

F. Blende and galena.

G. Tetrahedrite (argentiferous and auriferous), quartz, and mixed carbonates.

H. Quartz and mixed carbonates.

I. Calcite.

At any one locality, numerous gaps in the representation of these stages commonly occur.

Reverting to the earliest stages of this sequence: the earliest crystallization, of andesine, oligoclase, and hornblende, represents a typical diorite. The second or B stage, of magnetite, biotite, and some pyroxene, was succeeded by the C stage of orthoclase, apatite, titanite, chlorite, fluorite, and zircon. These stages, which replace the earlier minerals, in the same rock, are by no means simple alterations, as will be seen. A vast amount, if not the preponderant amount, of the elements representing each successive stage are new-comers; as, for example, in the second stage (B),

magnetite, and in the third stage (C), the potash in the orthoclase, the apatite, titanite, quartz, pyrite, fluorite, and zircon. If the minerals of B were segregated into a separate magma, which intruded in the diorite as dikes, they would be basic dikes high in magnetite, and without feldspar, related to types frequently encountered (pyroxenite). If the same were true of stage C, we should have had alaskite dikes of the familiar type, with the characteristic "essential" and "accessory" minerals of granite and alaskite. Such basic and siliceous dikes are usual under such circumstances; they are the "complementary" dikes, which are normal as later minor intrusions after a dioritic intrusion. No such dikes occur in these intrusions or their vicinity; aplitic phases do cut the older phases, but they are subordinate and non-persistent, and are mineralogically of the same character as the far more widespread replacements of older rocks by penetration of a new fluid magma; and all are included in the above scheme of rock-mineral sequence. May we infer that the original rock has actually been penetrated by the subsequent complementary (basic and siliceous) magmas, but that these had a large proportion of aqueous and gaseous constituents, so that they could and did penetrate and replace the rock to a far greater degree than they formed independent bodies? Such a penetrant magma I inclined to regard as belonging to the most gaseous phase (superpegmatitic).

Let us note the replacement of the original hornblende of stage A by pyroxene in stages B, C, and D. This should, according to all experiments, indicate a higher temperature[13] for these gaseous complementary subsequent magmas than at the time of the first crystallization; but the temperature evidently fell again before stage E—the copper stage—was reached. At Matehuala we have, essentially, the D-I stages, but not the B-C stages; and the passage from the D (lime-silicate) stage to the E (copper-bearing)

[13] The temperature of formation of pyroxene is higher than that of hornblende. See p. 80.

stage is marked by a change from pyroxene to hornblende, indicating a lowering of temperature, which must, therefore, also have taken place at this stage at Velardeña.

Barrell[14] has performed a useful service in distinguishing between contact metamorphism, which means the recrystallization of rocks, or the crystallizing of the old materials of rocks into new minerals, and contact metasomatism, in which foreign constituents are added to the recrystallized rock from the magma. The early interpretation of lime-silicate rocks, especially those formed at the expense of limestone near granite intrusions, was that they were metamorphic in the above sense, and so the term contact metamorphism was coined. Ore deposits formed in these rocks were termed contact-metamorphic deposits. They are, I believe (and I think this is now generally recognized), not metamorphic deposits, but metasomatic, and, therefore, should be so termed. My experience shows that while frequently they occur on or near igneous contacts, this occurrence is by no means an essential or inherent feature; they may occur within the intrusive rock or within the intruded rock, and may occur some distance away from an intrusion; and all this is also true of the lime silicates with which they are more or less closely associated. It is, therefore, more accurate to omit the "contact" from the term, and call them simply "metasomatic" or "replacement" deposits; and this classifies them clearly. They are entirely analogous to other replacement deposits; but as regards other replacement deposits in limestone, such as an important class of lead and zinc deposits, for example, they were deposited at a higher temperature, hence (1) the closely associated and sometimes partially contemporaneous[15] lime silicates, instead of jasperoid (silicified limestone), and (2) the greater proximity to igneous intrusions which come from the same source as the ore-solution magma, and are closely allied genetically with it.

[14] *Professional Paper* 57, U. S. Geol. Surv., 1907.

[15] With the metallic minerals.

At Velardeña, then, we may say that the original diorite crystallization was locally successively altered by replacement (not metamorphism) to first a more basic phase, and second to a more abundant more siliceous phase signalized by minerals containing volatile elements or minerals characteristically associated with these, and so on to a basic ore magma rich in iron, from which the ores were deposited in succession, till finally only quartz, calcite, magnesia, iron, and manganese carbonates were residual.

The replacement of an early partially or possibly entirely crystallized magma by a succeeding magma stage—notably the replacement of a more basic stage by a more siliceous stage, as exhibited at Velardeña—has not been generally recognized: but I am inclined to think it may not be uncommon. At Helvetia (Arizona), the earliest intrusion is abundant granite, consisting principally of quartz, feldspar, and biotite. Certain portions of this granite appear more basic, even of dioritic aspect in the field, and contain black apparently pseudomorphous areas. Microscopic examination shows, indeed, pseudomorphous aggregates after large hornblende or pyroxene crystals: and these areas prove to be fine fresh biotite, with apatite, rutile, muscovite, magnetite, quartz, and chlorite. Also, original oligoclase or oligoclase-andesine is found to be highly altered to or replaced by orthoclase, fine muscovite, biotite, quartz, and apatite.

The general order of crystallization indicated then, is: 1, oligoclase-andesine and pyroxene or hornblende; 2, orthoclase, quartz, muscovite, biotite, chlorite, zircon, apatite, and magnetite. In other words, the first crystallization, as at Velardeña, was a diorite, and this was replaced by a granite magma charged with volatile elements—a super-pegmatitic granite magma. It is likely that the granite owed its penetrant power largely to these volatile elements. Minerals containing them or known to be crystallized from them, like apatite, zircon, fluorite, and magnetite, which occur freely crystallized (idiomorphic) in granitic rocks,

have usually been held to be thereby shown the oldest crystallization in the magma; but this is not a safe criterion, since the phenomena of replácement often include the growth of isolated idiomorphic crystals, as I have shown in the formation of jasperoid by silicification of limestone (Fig. 91); and such an example (of the formation of quartz crystals in limestone in the initial stages of silicification) is probably analogous to the formation of these "accessory" minerals in granite, for these accessory minerals are also characteristic of pegmatitic and vein residues (see Chapter XII).

Petrographers have long described "resorption" phenomena—whereby, for example, the quartz phenocrysts of rhyolites have been partly resorbed by the still fluid mass; and in rhyolite at Tonopah I have shown how original hornblende crystals in a fluid magma were resorbed or replaced by an alaskitic residue. The phenomena described at Velardeña and Helvetia, however, are different: they represent the partial replacement of considerable masses of dioritic rocks by a later superpegmatitic granitic surge. What becomes of the replaced materials: for certainly lime at least has been removed in the replacement of andesine by orthoclase? It is apparently passed by the granite into its residual magma. Large calcite veins are in many districts the last phase of the magmatic sequence.

CHAPTER VIII

The Time Relation Between Rock Intrusion and Ore Intrusion

This chapter points out that ore deposits are typically localized along fissures of slight displacement originating immediately subsequent to an igneous intrusion; that subsequently, as a rule, there is long-continued faulting, due to the adjustments in position of the consolidating or otherwise moving magma. This association proves that metalliferous veins are a phase of igneous activity. The time required for ore deposition is in general analogous to that required for the intrusion of igneous rocks. The ore magmas are believed to develop only under deep plutonic conditions, in the zone of differentiation; therefore, they are distinct from the magmatic fluids represented by volcanic emanations.

SO FAR AS I HAVE EVER SEEN, all igneous rocks are intrusive, whether they are great domes or bosses or stocks, at the greater depths; dikes, masses, sills, laccoliths, domes, or plugs, at intermediate depths, or immediately below the surface; or overflows at the surface. I use the word intrusive in this broad sense to contrast the idea with the old conception that the deep-lying plutonic masses were part of the original crust of the globe, and were, therefore, in their original position and home—not migratory rocks which had come from somewhere else. I have observed many of these deep-seated masses; and personally I have never encountered igneous rocks that had not come from somewhere else, and that had not migrated upward through overlying rocks, as intrusives. This "somewhere" else is, of course, almost or quite invariably "lower down"; and more than that we cannot say. Certainly, however, the deeper igneous rocks bear evidence of upward migration on a broader and gentler scale than those which have penetrated higher up. This circumstance perhaps inheres in the very definition of these igneous-rock zones,

for those magma tongues which become intrusives at intermediate depths or at or near the surface certainly must have been impelled by a greater telluric pressure than is possessed by the plutonic magma masses.

As earlier suggested, a local concentration, in the deep magma, of those volatile constituents which very likely supply the main telluric pressure may furnish the special intrusive power which causes active local excursions up into the overlying crust; and if this is the case, then those magmas which reach the surface must have been unusually potent in this respect. Now, in those plugs of relatively limited horizontal dimensions which have ascended like up-reaching fingers from a magma mass below, the localization of the volatile and metal-depositing magmas which has been observed in the upper portions of deep-seated domes may be still more marked; and this may bring about a local intensity of ore deposition, above and near the plug. Rich ore-bearing districts of limited horizontal area will often be found to have depended on such conditions, as at Leadville and Aspen, in Colorado.

With the preliminary thesis that, for the purposes of my problem at least, all igneous rocks are intrusive, we may investigate to see if there is any definite relation of the period of intrusion to the period of ore deposition. The event of intrusion is a great critical and general determining factor. It disturbs and changes previous conditions of temperature and pressure in the magma and in the intruded rocks, makes it necessary that there be adjustments of position in the intruded rocks, starts crystallization in the intrusive magma if the net result of the change has been a lowering of the temperature, or starts resorption of already formed crystals if the net result has been—as it may be—an increase of temperature or a new magma mixture.

Given two masses of the same specific gravity, the overlying one a crystallized rock, from which the active gaseous elements have been long since eliminated, and the underlying one a still fluid magma at a temperature above that

"critical" for many of the components, which are therefore in a gaseous state, and containing other telluric more volatile gaseous elements which are seeking escape, the gaseous pressure or vapor tension of the magma, even if slight, will surely cause the magma to lift up and penetrate the solid rock; and the rate of this intrusion will depend upon the relative amount of gases (of vapor tension). Where the vapor tension is not excessive, and where it is widely distributed, the upward surgence will be slow and widespread; where concentrated, the magma will cleave upward in far less relative time, and even may arrive at the surface with every show of violence.

The blowing off of the tops of volcanoes by successive renewals of eruptive activity should be a sufficient object lesson to those who believe in the so-called "permissive" theory of igneous intrusion, as to the untenability of their views. True, the theory was earlier held that the water and other gases which produced these explosions were due to surface water, which penetrated down to the lava, was changed into steam, and so exploded; but this hypothesis has been shattered, for it has been shown that water cannot penetrate far down into the lava, being converted to steam almost immediately and returned to the surface; and that, moreover, large quantities of water and other vapors are given off from the cooling lava itself at the surface. Therefore, except in minor well-known instances, the cause of the explosions is the pressure of accumulated magmatic gases.

In an article published in 1916,[1] I arrived at certain definite conclusions regarding the relationship of the period of intrusion and the period of ore deposition, as the result of the examination of a number of instances which showed a similar sequence of phenomena. I shall here present these considerations in a somewhat different form, tending rather

[1] "The Relation of Ore Deposition to Faulting," *Econ. Geol.*, Vol. XI, No. 7, p. 601.

to present the general law first and the illustrative examples later.

Magmatic ore deposits, including mineral veins, usually depend for their localization upon fissures in the solid rock in which they form. In some cases, as in the replacement deposits (whether at moderate temperatures, the replacements with silica and lime gangue, or at more elevated temperatures, the replacements with lime-silicate gangue), the fissure which has served as a channel of access for the metal-bearing solutions is forsaken by such solutions, which penetrate the wall rock far and intensely. In other cases, especially where the wall rock is not readily soluble and replaceable, or where the ore magma was "aplitic" (see Chapter VII), the ores are deposited pretty faithfully along the channel, filling the fissure, if the solutions were concentrated, by a veindike; or, if the solutions were more dilute, replacing the shattered rock along the fissure to form an impregnation or replacement vein of the regular fissure type.

While my reader may be inclined to make the rule less sweeping than I do, if he has had much field experience he will agree that, in general, fissures, simple or intersecting, govern the localization of most orebodies. For that matter, not only do they govern the position of veins and veindikes, but in general it is true that they perform this function for dikes also. A complex of narrow dikes will be found, in their tabular form, which is like that of veins, and in their regular parallel or intersecting systems, which again correspond to those of veins, to resemble in pattern the ordinary fissure and fracture systems induced by dynamic stress in the solid rocks; and no other explanation of the form and direction of strike and dip of most of these smaller dikes is admissible (Fig. 64). Further evidence is often seen of the common control of both veins and dikes by these straight fissures, in the cases where veins and dikes successively occupy a fissure, which, repeatedly occupied

by either vein or dike, has been repeatedly reopened by renewed dynamic stress in the rock, and occupied again.

The cementation of a fissure by a vein or dike does not make it whole again, nor as strong as the unbroken rock; like a valuable dinner plate, broken and mended by cement, it will usually break, if under strain, along the old line. Once a plane of weakness is thus developed, the tendency is for it to remain always a plane of weakness. Thus, I have

FIG. 64.—Zimapan, Hidalgo, Mexico. An example of "linked" dikes. Dikes of Tertiary andesite (later andesite). Dikes lie in a hardened volcanic tuff formation, which is cut by earlier andesite dikes (not shown), also of linked habit: these in turn are cut by the dikes shown here. Mineral veins have an age intermediate between the two andesites. Detail from geologic map by G. H. Garrey, direction of J. E. Spurr, 1907.

noted (p. 282) in the Pañuela vein, at Tepezala, in Mexico, a case where a quartz-calcite vein carrying galena and silver has been reopened and occupied by a later rhyolite dike. Also, in the Stanley mine, at Idaho Springs, Colorado, I have described where the original intrusion along the main fissure was a dike (of bostonite): this was followed by the main vein formation (quartz, gold-bearing pyrite, galena, and chalcopyrite); later the fissure was occupied by another dike (of latite); still later, the fissure was again reopened,

with, as in the previous stages, some fault movement between the walls, and there was injected a breccia dike (see p. 853); and finally there was a scanty vein deposition (galena and chalcopyrite).[2]

In spite of these instances where the main dike occupied a given fissure at a later date than the main vein, the general rule is the reverse: the dike is first, and the vein later. This is a very common association—the subsequent vein runs along one of the dike walls, or both, or in the dike itself, or crosses from one wall to another, or perhaps parallels closely the dike, with a little slab or "horse" of country rock between dike and vein; or does several or all of these things in turn. Some intimate genetic dependence of vein on dike in these cases is commonly assumed; but there is none, the chief factor being the existence of the hospitable fissure repeatedly open to different calls. Take the case of the Stanley lode, above described—would it be the preceding bostonite dike or the subsequent latite dike with which the Stanley metalliferous vein was associated, according to the current theory? The fact is that this association by itself proves neither; but with the rule in mind that ordinarily the vein follows the dike, the earlier dike may, on general grounds, indicate a broad genetic relationship between igneous intrusion and mineralization, but no local or intimate connection.

Just as it is the rule (to which there are exceptions) that where a vein and a dike occur together, or side by side, the dike is the older, so in a broader sense it is the rule that where the deposition of ore takes place in a region of igneous rock, the ore is subsequent to the consolidation of the igneous rock with which it is associated, and characteristically the metalliferous veins form in the igneous rock as well as in the intruded rocks. There are again exceptions to this rule, but I think that all of my readers of experience will agree to it in general, without any necessity whatever for my citing any of the thousands of well-known examples

[2] J. E. Spurr, *Professional Paper* 63, U. S. Geol. Surv., p. 347.

which constitute the proof. Moreover, exceptional cases like the two (the Pañuela and the Stanley) which I have cited above, and which are not at all unusual, and the evidence cited in Chapter VI concerning Tonopah, where it was shown that the vein deposition which followed each lava intrusion was itself cut off by the next lava intrusion, which in turn was followed by another period of vein formation, and so on, show that not only is the vein formation characteristically subsequent to the intrusion of the igneous rock, but it is *immediately* (geologically speaking) subsequent.

The first stage of magmatic invasion, then, is that of the igneous rock, which *if possible* avails itself of fissure zones and fracture planes,[3] the most important of which are occupied by dikes. I am under the impression that the fissures occupied by these dikes are not usually fault fissures, or that if differential movement has taken place along these fissures it has been very slight, by which I mean a matter of a few inches or a few feet. This is a generalization to which we will note frequent exceptions. At Tonopah, for example, the Brougher dacite intrusion has taken place partly along fissure planes which had already become fault planes of no inconsiderable differential movement. Many of these were penetrated by dikes of the dacite.[4]

The second event in the history of intrusion and associated ore deposition is the formation of the metalliferous veins. As I above stated, the access and the localization of these veins is characteristically determined by fissuring which cuts through the igneous rock as well as the intruded rocks.

Now, I think, again, that my experienced readers will agree with me when I say that the fissures along which these veins have formed are not as a rule fault fissures, or

[3] Wherever fissures are not available, the upward intrusion will nevertheless take place. See pp. 860-863.

[4] J. E. Spurr, *Professional Paper* 42, U. S. Geol. Surv., pp. 73, 79.

if there has been movement it has been relatively slight—meaning a differential movement of the opposing walls, amounting to a few inches or a few feet. There are frequent exceptions to this rule, one or two of which I shall mention later: but it is not necessary to cite any of the thousands of cases to substantiate the rule. Frequently,

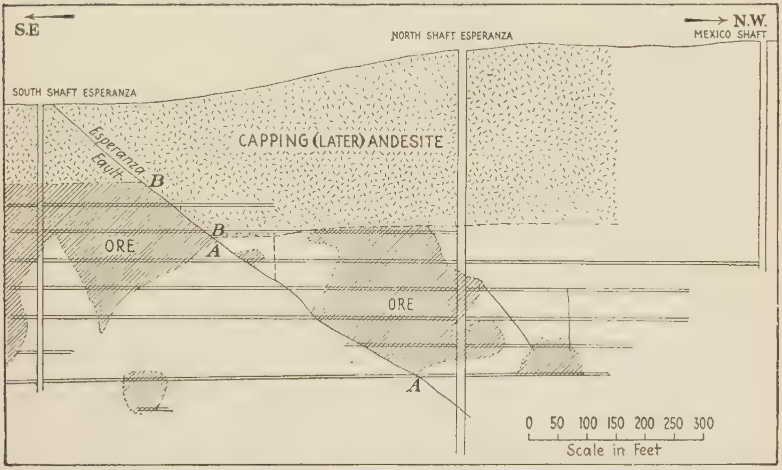


FIG. 65.—Esperanza mine, El Oro, Mexico. Vertical projection, on strike, of San Rafael vein. As drawn by J. E. Spurr, 1905, to determine amount of displacement on Esperanza fault. Total movement was determined as A—A, by matching oreshoots in the quartz vein, though the displacement of the "capping" andesite (B—B), previously accepted as the measure of faulting, was only one-third as great. Two-thirds of the fault movement took place before the andesite overflow, one-third after the flow. The solution of this problem, applied to finding the extension of the rich "West vein" orebodies, which had been lost at the fault, yielded in the succeeding years many million dollars profits in the Esperanza and the adjoining Mexico mine.

a slight displacement is recorded by the two walls, or pre-mineral movement is registered by striations, showing the beginning of faulting. In some cases, also—exceptions to the rule—the faults have developed to a considerable magnitude before they are cemented by the metalliferous veins.

The next step in the usual history of events which follow upon an intrusion, after the development of usually slight fault fissures and the subsequent ore deposition, is a con-

tinuation of rock movement, expressing itself in movement of one block upon another, producing faulting along fissures, which frequently results in a complex fault system. This movement often takes place in part along the veins: and the formation of a clay "gouge" or selvage along one wall or both walls of the vein, constituting the "good wall" so dear to the old-fashioned miner as a guide to follow, is often due to the grinding along one of these subsequent faults. Of course, the trust of the miner in such "walls" as an evidence of strength in the veins is often betrayed: one of the commonest errors in mining is to follow this fault slip, if it diverges entirely, as it often does, from the vein, and to leave the vein in the wall of the drift. Cross faults also typically develop. Observations in many districts indicate that movement along these faults is continuous or repeated, and may thus be extended over a very long period, frequently lasting, as at Aspen, Tonopah, Matehuala, and elsewhere, down to the present day, from the remote period of intrusion and mineralization which occurred millions of years ago, and whose ores have been laid bare to the surface, since then, by the erosion of thousands of feet of rock.[5]

Calculations based upon the materials carried by streams indicate that the area of the United States is being lowered at the rate of one foot in from 5,000 to 10,000 years, and probably between 7,000 and 9,000.[6] At Aspen the amount removed by erosion since the beginning of faulting has been estimated by myself at at least 15,000 feet, which, even at 2,000 years to a foot,[7] would give the enormous figure of thirty million years. Yet during all this time the faults of the district have been repeatedly moving, down to the present day, although the ore deposition was past and over

[5] The accompanying section (Fig. 65) from the Esperanza mine, El Oro, Mexico, serves as an excellent illustration of the long-continued and recurrent growth of faults.

[6] Pirsson and Schuchert: "Text Book of Geology," Part I, p. 47. John Wiley & Sons, Inc.

[7] Erosion in mountainous regions is much more rapid than the average.

many millions of years ago. A similar history is recorded in many other districts.

Therefore, we note that after intrusion a continuous or recurrent shifting of the rock blocks, one upon the other, takes place, involving the igneous rock as well as the intruded rock; begins and continues, in the case of the observed post-Cretaceous and Tertiary mining districts described, for many millions of years, down to the present time; and that ore deposition takes place typically at the very beginning of such movements or very soon after the intrusion and consolidation. This is true of all the various successive stages of ore deposition taken as a whole, as is displayed in many districts where certain sets of veins are superimposed upon earlier sets. Study of these successive stages indicates that a very considerable period was probably necessary for the complete series of mineralization phenomena; but all together they form but a single episode compared to the subsequent vast period during which the growth of faults, which at no time were again occupied by vein-forming solutions, kept steadily or recurrently on.

What is the cause of these enormously protracted fault movements, involving the continued and repeated adjustment of different blocks of rock? The areas of complex faulting, as at Tonopah, Aspen, and Leadville, frequently coincide with areas of intrusion or of mineralization, or both.

A clew to the origin of localized complex faulting (of at least one type) is shown at Tonopah, around some of the post-mineral (later than the ore deposition) volcanic necks, where many fault blocks, which have moved one upon another, are developed as a fringe or aureole around the intrusive necks, which themselves have not been faulted. Certainly in this case it was the adjustments in position of the intrusive rock which have produced the faulting in the rocks adjacent; and the recorded movements show that this faulting was caused by the settling down of the volcanic necks after intrusion, for the aureoles of faulted blocks

have been dragged down below the level of those rocks which are further away; moreover, the larger necks have had this effect to a greater degree than the smaller ones.

Study of the accompanying map (Fig. 66), taken from my Tonopah report, shows what an important factor in faulting such post-intrusive adjustments may be. These down-dragged blocks are most depressed around the intrusive necks of a certain lava, called locally the Brougher dacite, as is shown in the lower portion of the map, and most notably around the largest neck, which is in the lower right-hand corner of the map and which is called Mount Butler, although the depression around the neck of similar lava (Mount Golden) shown in the upper right-hand portion of the map is also very marked. But it will further be noted that the whole lower part of the map, which is the general area in which the Brougher dacite necks occur, is depressed relatively to the upper part of the map, in which these do not occur, and that this whole lower part is cut up by a complex intersecting system of faults, which divide the rock into blocks which have moved one upon another in a general irregular sinking, even when not closely connected with any visible neck or intrusion. Moreover, inspection of the down-faulted blocks around the volcanic necks proves that the problem is nothing like so simple as the sinking of the neck as a whole, for certain portions of the same neck have sagged far more than adjacent portions, as the contiguous fault blocks show. Therefore, a complex differential adjustment of the rocks following the intrusion of the Brougher dacite is shown, involving in general the whole area occupied by, underlain by, or immediately adjacent to the intrusions. This irregular adjustment also affected differentially the rocks lying between the necks, indicating more deeply buried (not now outcropping) intrusives of this same period, which caused their share of adjustment. In this map, it is shown that many of the fault fissures existed at the time of the intrusion, for in some places unfaulted tongues and points of lava from the necks run

FIG. 66.—Tonopah, Nevada. Intrusive volcanic necks and fault blocks. Shows relative displacement of different sets of fault blocks and their relation to the dacite necks. After J. E. Spurr: Professional Paper 42, U. S. Geol. Surv.; Plate VII.

out into and along the faults, so that some of the differential movement of the fault blocks took place before or at the time of local intrusion,[8] although the general sagging around the necks must have directly followed this intrusion. I have, therefore, summarized the faulting as follows, in my Tonopah report[9]:

"The faulting in this district is of extraordinary interest, for the origin, time, and cause are clearly understood. It is rare that any explanation other than a general unsubstantiated hypothesis can be applied to any particular case of faulting. Here, however, it is plain that the faulting was the result of adjustments of the crust to suit violent migrations of volcanic rock; that it originated with the swelling up of the crust and its forcible thrusting up and aside to make way for the numerous columns of escaping lava; and that after the cessation of the eruptions it was continued by the irregular sinking of the crust into the unsolid depths from which the lava had been ejected. It can readily be seen that all sorts of pressure (from below upward, lateral, and downward, by virtue of gravity) must have been concerned in such movements, and that the first faults were due rather to upward and lateral irregular thrusts, while the later ones (in many cases along the same planes as the first) were due to gravity. So reversed and normal faults are equally natural, and both occur frequently."

I further pointed out that the mapped area of faulting and depression consequent upon local igneous intrusion was only a little patch in a larger volcanic region similarly affected, whose boundaries were not even approximately known; that the fault-block movements were minor adjustments attending broader elevations or depressions; and that the explanation of these movements, both localized and more general, so conclusively demonstrated at Tonopah, must have a still wider application; and, therefore, that

[8] That is, a minor amount of the faulting belongs to movements antedating this period of dacite intrusion.

[9] *Professional Paper* 42, U. S. Geol. Surv., p. 80.

it was not far-fetched to extend this explanation as an hypothesis to the repeated down-warpings and uplifts, local and regional, which characterized this whole vast Great Basin region throughout the Tertiary down to the present day. During all this period, regional warping has been contemporaneous with folding and faulting, and with volcanic activity. My general conclusion was that while I had recognized in my earlier work in this region the coextension, both areally and chronologically, of volcanic intrusion and the heaving and breaking of the crust, and had conceived both as being due to a single unknown cause, in the light of the Tonopah studies it seemed fair to admit that the latter may have been the result of the former, as a general fact as well as in the Tonopah instance.

The Brougher dacite intrusions and attendant faulting which I have described above at Tonopah are not connected with the metalliferous veins of this region—they are entirely later phenomena; and no ore deposition, so far as we know, attended or immediately followed this particular volcanic outburst. It was one of the later instances of a series of many such outbursts, which came one after another during the whole Tertiary period; and the main veins at Tonopah, as I have described, are connected with earlier igneous (volcanic) intrusions. But the main veins at Tonopah, though situated in a region of such heavy, intense, and repeated faulting, filled fissures of very slight or insignificant displacement; while there were successive stages of later strong fault fissures which cut the veins, these fissures are either wholly free from vein deposition, or were at a certain definite stage partly cemented by vein formation of one of the later vein periods. The repeated intrusions and repeated periods of mineralization at Tonopah confuse the picture somewhat and prevent its being wholly satisfactory as a type example. But in general it may be stated that the fissures which the chief veins occupied were not only insignificant as faults, but they were the first fissures to form after the intrusion or

eruption of the igneous rock with which they were closely connected. The accompanying section (Fig. 67) of important Tonopah veins shows how slight was the fissuring movement, for the fissures scatter and disappear in depth. This phenomenon is a common one; also, fissures may

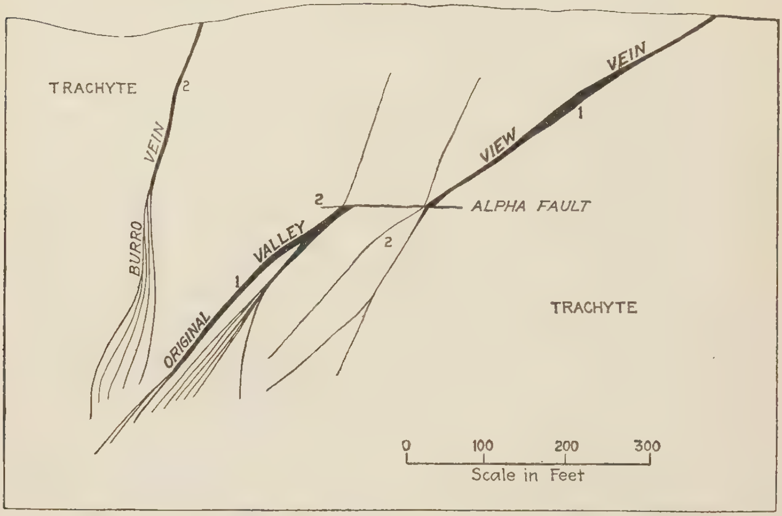


Fig. 67.—Cross-section of Valley View and Burro veins in trachyte, Tonopah, Nevada. Shows splitting and termination of a wide and rich vein—the Valley View—at moderate depth, without change of formation. The Burro vein yielded much ore near the surface. Also shows two vein periods: the original Valley View vein (1) was horizontally faulted, and the fault (2) was cemented by quartz of the second period. Quartz of the second period also formed a false extension downward of the upper segment of the original Valley View vein, as shown. The Burro vein is a second-period vein (2), and hence was not faulted by the flat Alpha fault. By J. E. Spurr.

scatter and disappear upward, as shown in one of the branches of the Camp Bird vein (Fig. 114). The case of fissures scattering and disappearing laterally is also a very common one. All these emphasize the fact that in these cases there was little or no faulting, and chiefly a tension or torsion permitting cracks of limited and irregular extent to appear in the rocks. This cracking in the trachyte, which

at Tonopah forms the wall rocks of the veins illustrated in Fig. 67, was so weak and so sensitive that in no case do the cracks appear to have penetrated downward to the glassy phase (Glassy trachyte) which lay at the base of this trachyte flow.

I therefore wish, connecting up earlier statements and principles laid down, to propose as a fact that, in general, metalliferous veins are among the first phenomena immediately succeeding the intrusion and consolidation of an igneous rock; that they typically occupy the first cracks and slight rifts formed by the adjustments due to the cooling magma; that their formation is effected in a very brief epoch of geological time; that, thereafter, the adjustment of the rocks (due to further movement, either up or down, of the underlying magma, to shrinkage on consolidation of the intrusive, and also the contraction of the intruded rocks due to gradual loss of acquired heat) produces typically faults of all degrees of magnitude, which will not be filled by veins unless there is another igneous surgence or invasion, and, indeed, another ore-magma surgence or invasion. Therefore it is that we find faults usually with little or no vein filling, and vein fissures usually with little or no faulting.

This relation proves that metalliferous veins are a phase of igneous intrusion—*they have the same general relation to the main rock magma as have subsequent dikes of aplite or pegmatite in connection with granitic intrusions, or any of the other relatively highly specialized magmas which follow up along the path broken by the main rock magma.* The ore solution, then, is by its relationship shown to merit the classification which I have elsewhere given it as a highly specialized form of igneous magma.

In the case of the plutonic magmas, I have made the deduction that the ore magmas, since their temperature of consolidation is less than that of the rock magmas, would ordinarily ascend past the upper surface of an igneous-rock intrusion, and be deposited in successive and orderly zones

one above the other, or one outside of the other. Such conditions imply a complete opportunity for deposition, in a single general horizontal or vertical range, of the available metal or metals peculiar to the given zone. Where, therefore, we find a large amount of mineralization of a simple type, with no attendant intrusive rock, as in the lead and in the zinc deposits of Missouri, we shall be inclined to refer the mineralization to the plutonic type, and assume that the related intrusion lies some thousands of feet beneath. In such cases we may find that the dynamic history tells the tale as clearly as if the igneous rock were observable, if this dynamic history shows the same sequence as that observed in districts like Tonopah, where the igneous rock is present, and where it may be studied in connection with the mineral veins. At Flat River, in Missouri, for example, I have observed that the ores were controlled by vertical or steeply dipping fissures, from which the ore solutions spread out and replaced the strata, especially limestone, along favorable beds, while subsequent fissuring, which grew to faults of small and intermediate magnitude,[10] is quite unmineralized. This marks the magmatic type of ore deposit, and indicates an intrusion or magma surgence beneath, just previous to the ore deposition: but that it was a broad and relatively gentle upward invasion is shown by the relatively slightly disturbed position of the sedimentary rocks.

The copper deposits of the Keweenaw peninsula, in Michigan, are also of this type. The mineralization is simple and intense and belongs to the copper zone: and the ores have formed in fissures and fracture zones of little or no displacement, in a thick series of Cambrian or pre-Cambrian (Keweenawan) basalts and interbedded conglomerates. These fracture zones were mainly localized in certain beds, either of basalt or conglomerate, and I

[10] In numerous cases the fault displacements are up to 25 and 50 feet, and in one case 500 feet. The main strike of the post-mineral faults is parallel to the main trend of pre-mineral fissuring in the Flat River mine.

have surmised that the strains which caused them were due to the steep tilting which attended the formation of a great fault—the Keweenaw fault. The fault itself is not known to be mineralized: therefore, the vein formation appears to have followed the first slight movement in the rock disturbance, which continued, in successive stages, during a vast period of time—down to the Devonian or later. In this case, also, the fact that the ore solutions gained access through the first slight fissures, and did not reappear in all succeeding time, marks the magmatic type, although it is not known to which of the numerous intrusives of this great period of igneous activity the deposits are most closely allied.

These two cases of plutonic magmas and their special types of ore deposits are intended only as a digression, to illustrate how the dynamic test may identify their connection with intrusions even when the intrusion is not visible, or identified as related. I will now, having sketched out the rule, and its use, when established, as a criterion, mention a few cases which go to demonstrate the rule.

Although it may seem somewhat in the nature of a repetition, I wish to refer the reader in this connection again to the mining districts of Matehuala and Velardeña, in Mexico (see Chapter V). At Matehuala, the ores of copper (and less conspicuous ores of lead, zinc, arsenic, gold, and silver) were deposited along and near fissures in and near a monzonite intrusion, especially near the contact. These fissures were marked by little or no differential movement. After the ore deposition was finished, fault fissures developed. The very first of these were cemented by calcite, which was the very last phase of the mineral sequence which marked the vein formation, but afterward one at least of the faults had an enormous growth, and was never filled by any vein material whatever, although it stood open for the whole subsequent period—a period apparently vastly longer (one would infer thousands of times longer) than the time consumed for the ore deposition. This again

is the earmark of the magmatic ore deposit; but in this case no evidence of this kind is necessary for this explanation to carry conviction, since the ore deposits, with lime silicates, are grouped around and in the slightly older monzonite in a way which is typical of so-called "contact-metamorphic" deposits. At Matehuala, however, the growth of this great fault does not mark subsidence, but elevation (see Chapter IV). It forms one side of a pronounced domal structure of very limited areal extent, whose three other sides are formed by domal upfolding of the strata; and on account of the location of this dome in the region of the earlier monzonite intrusions (now exposed, together with their attendant ore deposits, by deep erosion) its formation is believed to be due to a further slow upward pressure of the still unconsolidated portion of the magma plug, very deep down.

In Velardeña, also, ores of copper, gold, arsenic, etc., were formed along fissures of very slight faulting movement which took place after intrusion of dioritic rocks in limestones; and these fissure veins, and replacement deposits dependent upon fissures, were formed both in the igneous rock and the intruded rock, and sometimes chiefly along the igneous contact—representing again, in the last-named case, the so-called "contact-metamorphic" type. Subsequently, heavy faulting developed, the earlier fault fissures being cemented by barren calcite, as at Matehuala, the later and heavier ones quite uncemented. Here, again, these are not faults of subsidence, but of uplift, for the mountain range in which these deposits occur is a dome or "anticlinal range of deformation" (although the dome structure has been impressed on previously folded and planed-down rocks); and the domal growth has been assisted by the faulting. The areal correspondence of this domal growth to that of the earlier intrusions, as at Matehuala, and the circumstance that, as at Matehuala, the growth of the dome began very soon after the intrusion, lead again to the conclusion

that the cause of the doming is the upward pressure of an unconsolidated magma plug or neck at great depth.

In the Georgetown silver-lead-zinc district, in Colorado, fissure veins are genetically connected with the intrusion, in the early Tertiary period, of alaskitic and granitic dikes of the intermediate zone, with "quartz-porphyry" texture, into pre-Cambrian granites and gneisses; and in all cases their formation followed the intrusion of the dikes. Both dikes and veins occupy fissures showing little fault movement, the amount varying from a few inches up to a few feet. Subsequent to the various stages of vein formation, the fault movements continued, largely along the same planes, and have resulted in uncemented fissures, whose fault movement varies from a few feet up to (exceptionally) a few hundred feet. Both pre-mineral and post-mineral movements have been approximately in a horizontal direction; so that if, as appears to be the rule, they are due to magma adjustments subsequent to intrusion, we may infer horizontal movements in the underlying magma, which, either by its forward creep or its shrinkage back upon cooling, has caused this relatively slight horizontal adjustment of fault blocks (see p. 740, Chapter XVI).

In Leadville, where the orebodies appear to be of about the same age as at Georgetown, and are associated with similar intrusive rocks, the ore has formed largely by replacement of limestone and dolomite beds, especially beneath intrusive sheets or sills of igneous rocks similar to those at Georgetown—"porphyries," representing the intermediate depths. Both intrusion and subsequent ore deposition have been on a very large scale. The district is broken into blocks by important faults, which have faulted both the igneous sheets and the orebodies, and so are post-mineral. The localization of the ores is controlled by earlier steeply dipping fissures of relatively slight fault movement. Along these slight fault fissures ore has been found in many instances to occur in shoots, in limestone or dolomite, under different sheets of igneous rock, lying one below the other,

and even under a relatively thin quartzite bed, which has performed the same damming-back function as the igneous sheets. In this way the irregular shoots of ore may be in some cases followed down along the controlling fissure through an upper dolomite (of Carboniferous age, and 200 feet thick), a quartzite (about 50 feet thick, and of Devonian age), a lower dolomite (of Silurian age, and about 140 feet thick), and a basal quartzite (of Cambrian age, and about 100 feet thick), into the underlying pre-Cambrian granites, gneisses, and schists. In the granites and quartzites the orebodies are represented by steeply dipping or vertical fissure veins, often marked, but of very slight economic importance; while beneath the intrusive sheets, which have dammed back the solutions, these ores have extensively replaced the dolomites, the largest orebodies being under the uppermost large igneous sheet, in the upper (Carboniferous) dolomite.

The above description is from my own studies. The slight fault fissures which I found to have been responsible for the access of the ore solutions had, to be sure, in at least the one case that I worked out (Fig. 68), a fault movement of about 100 feet before the ore deposition; and ordinarily this would be considered by no means a slight fault; but it is relatively slight for the Leadville district, for the faults which formed after the ore deposition had characteristically many times that amount of movement. In some cases a pre-mineral fault also had a very extensive post-mineral movement; in others the later faults, subsequent to the ore deposition, were along fissures different from the pre-mineral ones, which therefore stopped growing at or near the time of the mineralization.[11]

[11] I shall not attempt to cite the earlier opinions of Emmons, whose interpretation of the geology of the ore deposition was different. Development work subsequent to his studies long ago convinced the local engineers of the origin of the ores by ascending solutions; while the fact that the oreshoots developed along small fault fissures, after the beginning of the faulting, was possibly my own discovery, but it has been since confirmed by engineers at Leadville.

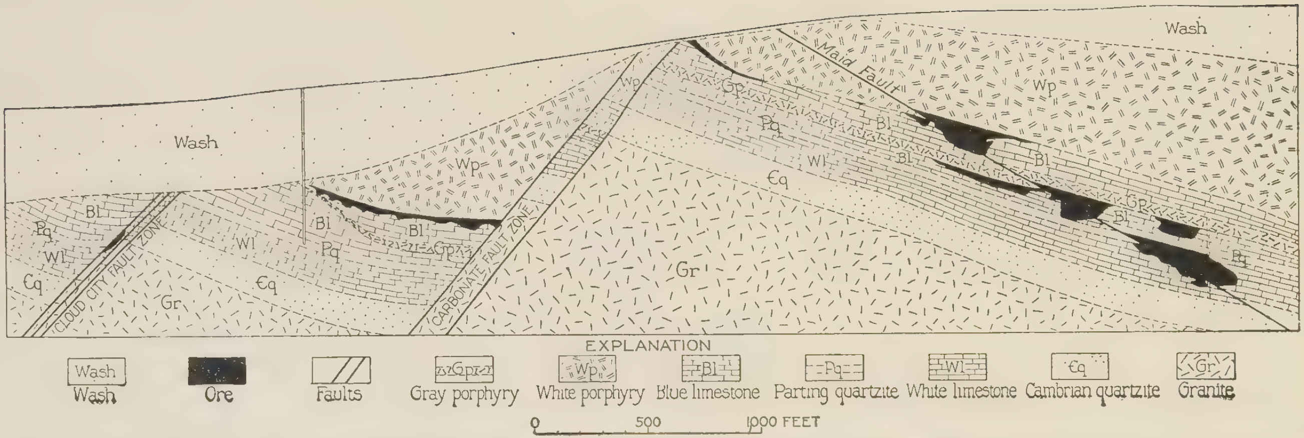


Fig. 68.—Leadville, Colorado. Accurate vertical cross-section drawn through a line crossing Carbonate Hill and Down Town districts, showing the formation of orebodies along the pre-mineral Maid fault, especially at its intersection with impervious formations above. The large faults shown—the Carbonate and Cloud City faults—are essentially post-mineral. By J. E. Spurr, from his own surveys, 1907.

The intrusive igneous sheets connect with steep or vertical dikes, which have been the channels through which the rock magmas ascended from the depths; and from these they spread out as sheets along favorable and easily split horizons of the sedimentary rocks. The habit of the intrusive rocks, it will be seen, is much like that of the ore, and for the same reasons. There were two chief separate intrusions; the first of an alaskitic porphyry, the second of a monzonitic porphyry; but there was only one period of ore deposition, so far as I have ascertained, in the portion of the district shown in the cross-section. This ore deposition followed directly after the second igneous intrusion, and seems to be to a certain extent associated with it as to general distribution. The primary or original ores were galena and blende (the former silver-bearing), and pyrite.[12]

The profound and long-continued faulting attended the uplift of the considerable mountain range (the Mosquito range), on the flank of which the Leadville mining district lies; and the summit of the range is formed by the most profoundly up-faulted block of all, the fault which bounds it on one side—the Mosquito fault—having a vertical displacement of 2,000 to 2,500 feet. The coincidence of the highest part of this great up-tilted block with the crest of the range, carefully studied, appeared to me to admit of no other explanation than that erosion has not yet counterbalanced the surface inequalities produced by faulting and tilting; that the faulting, therefore, has continued up to a relatively recent time, if not actually to the present.

We have, therefore, in recapitulation, in the Leadville district the intrusion of igneous rocks, followed by the beginning of fault-fissuring: these fault fissures at an early stage were occupied by metal-bearing solutions, or ore magma, which formed the ore deposits in one geologically brief epoch. Subsequently, the faults kept on growing, from the period of ore deposition (which may be put in

[12] The gold-bearing portion of the district presents a separate problem, not here attacked.

the early Tertiary) nearly or quite down to the present time. Both ore deposition and faulting, it will be observed, were subsequent to and in a way probably consequent upon the igneous intrusion; and the faulting is, therefore, probably due to the adjustments of the underlying magma. The faulting in this case, however, does not mark a subsidence after eruption, as around the Brougher dacite volcanic necks at Tonopah, but a steady subsequent uplift, as at Matehuala and Velardeña; therefore, it connotes a continually rising plug or belt of the magma.

I have cited the Aspen, Colorado, ore deposition in each of two preceding chapters: In Chapter IV as an example of the growth of domes, and in Chapter V as an example of the sequence of metalliferous veins. I prefer to illustrate my successive theses by well-studied types such as these, rather than to take a poorer example because I have not mentioned it before. I will, therefore, now cite Aspen again as evidence as to the problem of this chapter—the problem of the critical period of vein intrusion. Aspen is not many miles distant from Leadville, but in a distinct mountain range. The sedimentary series is the same as at Leadville, with the addition of a great thickness of subsequent strata, which at Aspen overlie the formations described at Leadville. There are intrusive rocks, of the same period as at Leadville (early Tertiary); and, as at Leadville, they have spread out as sheets in the sedimentary rocks, and these sheets are connected with the depths by cross-cutting dikes. One of the intrusive rocks is like the earlier intrusive porphyry (alaskitic) at Leadville, and probably from the same reservoir. The other, a diorite porphyry, is an outlying sheet from a great intrusive mass which forms the Elk Mountains, which lie a short distance to the west. The shove of this Elk Mountains intrusion caused close folding and faulting in some parts of the Aspen stratified series. At about the same time, the Sawatch range, on whose west flank Aspen lies, was gradually uplifted, by a force which

in Chapter IV I have argued to be an uprising ridge of magma below; and this uplift was accompanied by the slipping of one upturned stratum on another, producing important "bedding faults." A still third type of rock deformation which affected this little area was a very local doming-up, hardly more than a mile in diameter, while the amount of up-doming, as measured by the disturbed rocks, reached about the same figure. This doming was partially accomplished by up-folding of the strata, but the rock involved by this local uplift soon broke into many fault blocks, constituting a fault-complex not often paralleled (Fig. 44), and these fault blocks moved one upon the other in the process of uplift. I have given my arguments in Chapter IV that this local up-doming could have been caused by nothing else than a slowly uprising magma plug in depth. Thus, the mining district in general contains a complex of faults, traceable to at least three causes, but all of them being due to the disturbances of magma migration. These faults, as well as the folding, appear to have taken place practically entirely subsequently to the intrusion of the igneous sheets and dikes of the district, thus carrying out the general rule, above stated, that faulting is subsequent to intrusion.

Ore deposition was of silver-bearing galena, blende, and rich silver ores. The ore deposition began after the beginning of faulting, and it was, therefore, these fissures, following upon the intrusion, which gave access to the ore magma from below; but a deviation from the strict type is shown in that the ores did not form along the first fissures, when little or no fault movement had taken place, but after considerable faulting. Leadville begins to show to a slight degree this deviation from the strict type, in the deposition of ores along fissures which had attained a fault displacement of, in some instances, a hundred feet; but Aspen records a still further deviation, in that faults of still greater displacement have been mineralized to form veins. The

highly faulted domed-up area in the center of the Aspen district, which was the chief center of disturbance, became also the chief center of ore deposition. The ores are shown by local data to have come from below, and were mainly precipitated, not by the siliceous rocks—granites and quartzites—below, but by the dolomites and limestones of the Silurian and Carboniferous above, precisely as at Leadville; not so much spreading out along the strata (at least not to so marked an extent) as at Leadville, but forming, although by replacement, more closely in the vicinity of the fault channels. The ore deposition, which, as above stated, occurred after a considerable amount of this complex faulting (amounting in some cases to several hundred feet displacement) had gone on, occupied, according to the usual rule, a definite and geologically very brief period, and was then through forever. But the fault movements continued, and in fact reached down into post-glacial time; and it is certain that some, if not all, of them are still undergoing growth and adjustment. One of these faults, which may be taken as an illustration, had a dislocation or displacement (as measured on a vertical plane) of about 750 feet, of which about 350 feet was pre-mineral and 400 post-mineral. The ore deposition consisted of three successive stages, as mentioned in Chapter V: 1. Barren barite veins; 2, rich silver ores; 3, galena and blende. Had these stages stretched over any considerable period of geological time, this period would have been recorded as a section of the constantly developing fault movement; but scarcely more than a barely perceptible faulting is recorded during the whole period of ore deposition. In other words, the entire ore deposition took place along the growing fault within so short a space of time that it seems almost a mere point as compared with that occupied by the whole steady faulting. The fact that ore deposition of this magmatic type is accomplished, geologically speaking, in so short a space of time as to be almost too small to measure when compared with the

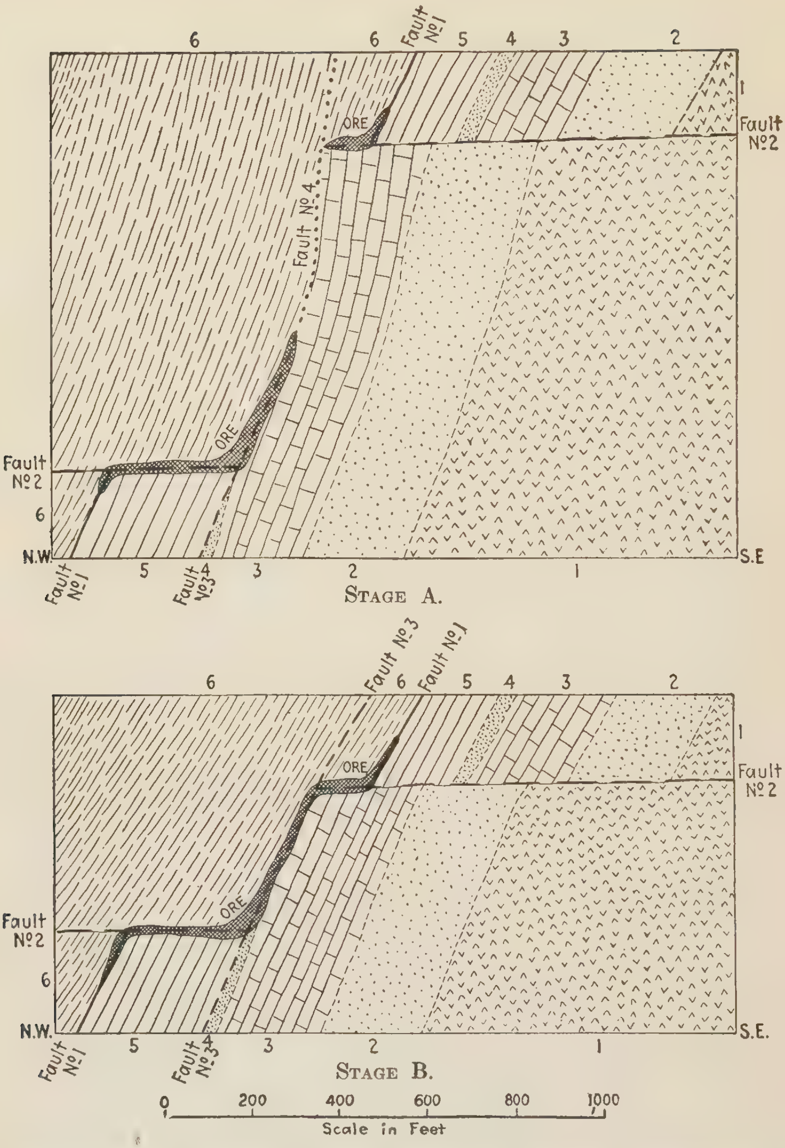
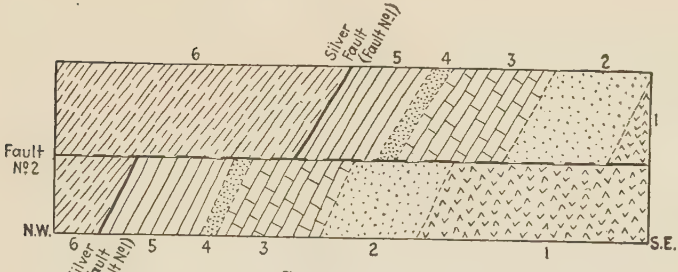
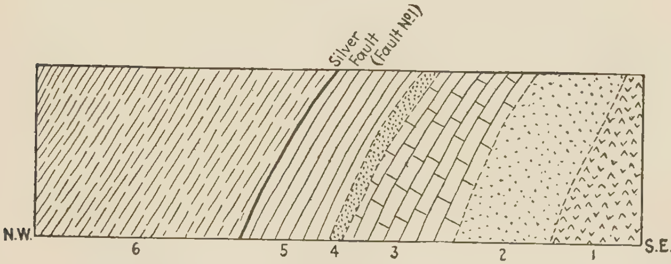


FIG. 69.—Aspen, Colorado. Vertical cross-section through Smuggler shaft. Shows (A) present structure, worked back in geologic history in successive stages (B, C, D, and E.) 1, pre-Cambrian granite; 2, Cambrian quartzite; 3, Silurian dolomite; 4, Devonian quartzite; 5, Carboniferous dolomite and limestone; 6, Carboniferous shale; 7, Tertiary intrusive sheet of rhyolite porphyry.

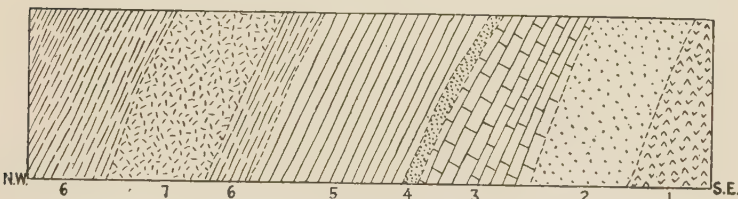
E (Stage 1) shows rocks after Tertiary tilting consequent upon the uplift of the range, and after intrusion.



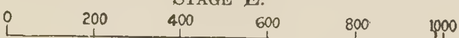
STAGE C.



STAGE D.



STAGE E.



D (Stage 2) shows same section after development of Fault No. 1, nearly parallel to bedding, but slightly oblique and of immense displacement. Note that this cuts out of the section the upper part of formation No. 5, all of formation No. 7, and an undetermined thickness of formation No. 6.

C (Stage 3) shows same section after development of Fault No. 2, here shown parallel to its strike. Actually it dips 30° toward the reader. This section naturally portrays only one element of the fault movement.

B (Stage 4) shows same section after development of Fault No. 3 and subsequent deposition of metallic sulphides and gangue minerals.

A (Stage 5) shows same section after development of Fault No. 4, later than ore deposition, and along much the same plane as Fault No. 3. Present stage.

These sections show the development in various stages, but there is reason to believe that the development of the structure was not carried on by jerks, but fairly continuously. The working out of this structure made possible the discovery of new orebodies after the mine had been given up as exhausted, and prolonged the life of the mine for years. Sections by J. E. Spurr, 1908.

time which was occupied by other geologic events, of both earlier and later periods, I was, I think, the first to point out.[13]

At Aspen, I believe the relative time required for a given stage of ore deposition to be more comparable to that required for the injection and solidification of an igneous dike or sheet than anything else. While figures in regard to such geologic time are even worse than the average statistics, some rough and preliminary working idea may perhaps be formed. The particular fault at Aspen which is used above as a criterion of the relative time occupied by ore deposition and faulting is one of a series of faults shown in the Smuggler mine, and originated after the development of two earlier sets of important faults, which the latest fault in question has in its turn faulted (Fig. 69). Let us grant—which appears approximately correct—that the total history of faulting was synchronous with the total history of uplift, and consequently with the erosion of 15,000 feet of strata which overlay the Aspen district before the uplift. On page 340, Chapter VIII, the rough figure of thirty million years was mentioned as the assumed time interval, on the basis of known rates of erosion. Let us further assume that this latest fault in question—the third of an important sequence of three—occupied approximately one-third of the time consumed in the grand total of faulting (and erosion), or ten million years. The 750-foot recorded movement on this fault would then have proceeded at the average rate of one foot in about 13,000 years; and the relative time indicated by the almost imperceptible fault movement during the different stages of ore deposition, if we liberally estimate it at a foot, could hardly have been more than the corresponding figure of 13,000 years. Assuredly, these figures have little precise value: but it is certain, from the consideration of the amount of erosion, that the fault movements have gone on for millions of years, while the

[13] "Ore Deposition at Aspen, Colorado." *Econ. Geol.*, Vol. IV, No. 4, 1909, p. 301.

several stages of ore deposition in this case can at most be estimated in tens of thousands,[14] a conception which is as close to the period required for the similar phenomenon, a dike injection in depth, as anything we can reach.

While making this comparison, however, of the time occupied by a magmatic vein formation with that occupied by an igneous intrusion, we shall have to recall some of our earlier conclusions as to the act of intrusion. If my reasoning in Chapter III is correct, then the intrusion or slow upward surgence of plutonic rocks, such as granite, with attendant "feeler" dikes into the overlying crust, may be and usually is a vastly slow process, keeping pace often with the progress of erosion, since in some cases it appears that the telluric pressure in the rising magma is insufficient to overcome the pressure of the weight of overlying rocks, except as this is lessened by erosion. Yet the upper contacts and fringing dikes of such a slowly upwelling plutonic magma will show the same intrusive phenomena as a lava dike near a volcano; but while the latter may have been injected in a day, a dike of the former (plutonic) type may have been a hundred thousand years in forcing itself into a fissure. It is probable, therefore, that typically the act of ore deposition takes place in less time than many plutonic intrusions, and in more time than some surface intrusions.

The general rule that veins fill fissures of slight displacement—that is, the first fissures formed after the intrusion of an igneous rock—indicates that in general the igneous rock and the specialized ore magma are close together in depth, so that the first adjustment fissures of the consolidating intrusive tap the latter. The cases where faulting has

[14] The Aspen example represents only a single (very illuminating) type; other examples show marked fault movement between two closely related stages of ore deposition, as the Tiro General mine (Fig. 59), where there was a fault movement of 80 meters between the blende stage and the chalcopyrite stage, and the Great Gulch mine, at Silver Peak (Fig. 11), where there is a fault of five feet between the plutonic gold-quartz stage and the auriferous arsenopyrite stage. Ore deposition and faulting have, therefore, each variable speed, as already concluded. Each individual mineral injection, however, appears to have occurred suddenly.

made greater or less progress before ore deposition occurs probably mean that the earlier fault fissures had failed to tap an ore-magma basin, possibly because it was situated at a somewhat different point from the source of the rock magma, and could be tapped only by an extension of the fault-fissure system; or it may mean that the beginning of the faulting was at an altogether earlier period than a subsequent renewal of intrusion and ore deposition (see Chapter XVI, succeeding).

Where an igneous intrusion is not followed by any mineralization, it may mean that the fissures subsequent to the intrusion have not tapped the ore-magma basin, or it may mean that there is no ore-magma basin. Certainly, the highly specialized nature of the ore magma indicates that it will be gathered together in the depths only here and there, and will have a far narrower extension than that of the mother magma or the principal rock magmas into which this may split. The vein formation following the later rhyolites at Tonopah, for example, is without valuable ore deposition; but at Divide, four miles from Tonopah, this period has produced some valuable ore, and at Goldfield, thirty miles away, the ores of this period appear to constitute the chief source of the riches of this great camp; and this seems to show that while a large underlying area in depth was occupied by the rhyolitic rock magma of this period, the ore magma belonging to the same general period of differentiation and intrusion was segregated mainly into certain pockets or basins beneath the solid crust.

Study of the frequent close relationship of ore deposition to local up-domings, which we have considered in Chapter IV, and the study showing the concentration of plutonic ore deposits in the upper portions of plutonic bosses which have caused up-doming, and in the pushed-up rocks immediately above,[15] indicates that pockets or basins of this often volatile and buoyant specialized or residual ore magma may occur in the top of the furthest up-reaching portions (domes

[15] B. S. Butler: *Econ. Geol.*, Vol. X, pp. 101-122, 1915.

or plugs) of the irregular upper surface of the magma, against the solid overlying crust. These appear to act as natural traps. Yet the frequently indicated relative buoyancy of such ore magmas is plainly not always due to minor specific gravity, for I have presented evidence in Chapter II indicating that some of the ore magmas were of very considerable specific gravity: as a more universal reason, the buoyancy of these ore magmas (especially of the pegmatitic and superpegmatitic types) must be due to accumulated volatile elements, like compressed water gas and those other telluric gases which escape, when released to the surface, as volcanic emanations.

The study of domical structures, therefore, assumes an importance in the study of mineral veins, as well as of oil pools, and for the same general reason. Such high upreaching pockets may conceivably thus be sought by various lighter terrestrial fluids and gases, of perhaps diverse origin. In the famous salt domes of Texas and Louisiana, petroleum, gas, sulphur, and salt waters occur, and, moreover, there has been a little deposition of metallic sulphides. It is not absolutely necessary to assume that all these have a common origin. Even the gases contained in such domes may conceivably be of mixed origin, some immediately telluric, others derived from chemical reactions in sedimentary rocks; and the salt waters may possibly have a similar mixed origin. It is difficult, it seems to me, to explain the helium locally found in considerable quantity in gases under similar conditions (as at Petrolia, in Texas) except by considering it of direct and profound telluric origin, but the associated inflammable gases are usually assigned to an ultimate organic origin.

The period of fault fissuring between an igneous intrusion and the succeeding ore-magma invasion has been shown in the exceptional Aspen case to have been really very long. The constant growth of the dome at Aspen, with its implied continued up-pressure of a magma body in depth, during the ore deposition, shows that the ores are not so closely

related to the intrusives now exposed as to the major deep-seated mother magma. The orebodies may then be held to depend upon practically plutonic conditions. It therefore appears that the close succession of a certain case of ore deposition to a now visible intrusion depends upon the propinquity of the site of ore deposition to the original deep magma dome in or near which the ore magma was accumulated, and not its propinquity to far-flung dikes and sheets from or from near this dome or reservoir. If this conception is correct, the sequences of intrusion and ore deposition will most often be close one upon the other in the case of plutonic intrusive rocks, now exposed, with their associated ore deposits; and will show an increasing number of wider and wider variations from the rule as the intrusion and subsequent ore deposition represent higher and higher horizons in the crust, both having migrated further and further from the mother domes or reservoirs. I believe that a little reflection will show that this is the case: that ore deposits connected with plutonic rocks, occurring in them or in the intruded rocks above, ordinarily occupy fissures of little or no displacement. This rule should, therefore, apply most closely to tin veins, those of tungsten and molybdenum, the whole group of commercial pegmatite veins, and gold-quartz veins of plutonic texture, like the California-Appalachians-Ontario type.[16]

Those copper deposits which are intimately associated with intrusive rocks whose texture shows them to belong to the lower or lower middle zone—granular and fine granular, verging toward porphyritic—should show the close sequence of ore upon associated intrusive rock with a somewhat less but still average good fidelity; and, therefore, the exceptions

[16] Moreover, faulting itself, in so far as it is due to magmatic adjustment, should be most characteristic of the more superficial intrusives and least so of the deep-seated igneous rocks; and I believe that reflection will deduce the conclusion that this also is actually the case; and if it is true, it provides a valuable check upon my conclusion that most faulting is caused by magma movements, whether by the disturbances of intrusion or by subsequent adjustment.

to the rule of ore deposition in fissures of little or no fault displacement should be rarer than for the upper mineral zones, but more frequent than for the plutonic types mentioned above. Among deposits of this copper zone, those grouped around an igneous dome or plug are conspicuous, forming the unfortunately called (as we now can see) "contact-metamorphic" type, in most of which, as far as my experience goes, the ore deposition has been controlled by definite fissures, preferentially localized near the contact on account of the post-intrusion adjustment movements of the igneous mass, which has produced the openings—but also often occurring within the igneous rock itself. These fissures are usually, in my experience, characterized by little or no fault displacement—they are the first fissures after intrusion, as is shown by the development of extensive subsequent faulting.

The zinc, lead, silver zones, which overlie the copper zone, though in general conforming to the rule that the ore follows close upon the heels of the igneous intrusion, should show a more frequent and wider divergence in point of time, from their associated and earlier intrusive, than do the copper ores, and should therefore, more often break away from what is always the rule—a breaking away illustrated at Aspen.

So much for the plutonic sequences of ore deposits. The less fully understood superficial division of mixed orebodies associated with igneous rocks formed near or at the surface calls for detached consideration (See Chapter VI); but previous deductions (Chapter V) would argue that both ore magma and rock magma had usually traveled upward far from the still relatively plutonic mother reservoir, and, therefore, that there will be frequent divergences from what is always the rule, and that the usual cases of veins in fissures of little or no displacement will be interspersed with cases of ore deposition along considerable faults. Thus, among Nevada ores of this group or division, Tonopah and Goldfield, where the ores occur along fissures of little or no displacement, will represent the rule, and the Comstock

Lode, where the ore cements the fissure of a heavy fault, will represent the exception. We shall hardly, however, expect to find the plutonic lodes, like those of tin, tungsten, or plutonic gold quartz, formed in faults of the great dimensions of the fault in which the Comstock occurs.

At El Oro, in Mexico, in the Esperanza and adjacent mines, there are two veins which run parallel and within a few hundred feet of each other: the main San Rafael vein, which is upward of 20 feet wide, and the West vein, which is perhaps five feet wide on the average (Fig. 70). Both contain ores of gold and silver: but the West vein was many times richer than the San Rafael, which was a relatively low-grade ore. Both of these veins were formed subsequent to an andesite intrusion, and occur in the andesite and the intruded rock (which is shale); and are earlier than a subsequent andesite, which came up as an intrusion and overflowed on the surface, forming a "capping" to the veins. The rich West vein has formed in a fissure of little or no faulting, but the San Rafael occupies a marked fault. Taking this fact in connection with the consistent difference in the nature of the filling, I think this may signify that the two fillings were of different age: so far as local evidence goes, it is difficult to decide which was the earlier. A similar association of wide low-grade quartz veins, with parallel narrower high-grade veins of the same general type (gold-bearing quartz veins, containing also galena, blende, and chalcopyrite), is found in the Pispis district in Nicaragua, where the veins also lie in andesite of probably Tertiary age, like that at El Oro. In the Nicaragua district the higher-grade veins are apparently the younger (see p. 665).

An extreme case of the divergence, in point of time of invasion, between the metalliferous vein and the closely associated intrusive rock is the one I have described at Tepezala in Chapter V, where the principal veins of the district occur in fault fissures of considerable displacement on opposite sides of an older volcanic neck which had been

rendered schistose in the interval between its intrusion and the faulting which preceded the ore deposition. The ore

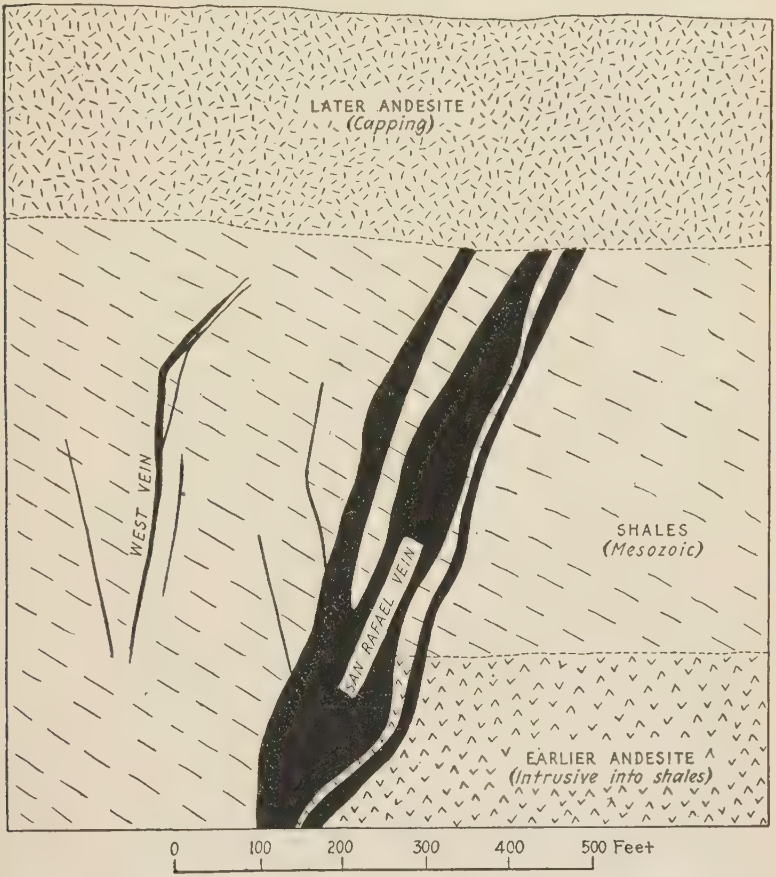


FIG. 70.—Esperanza mine, El Oro, Mexico. Cross-section (looking north) through veins, showing main (San Rafael) vein, and auxiliary West vein. The San Rafael is a quartz vein in which only portions have been ore (lower-grade). Note that it is a fault-fissure vein. The small West vein, of high-grade ore, has yielded far more profit than the San Rafael. Note that the West vein practically terminates, both above and below, as correctly represented.

deposition here is of the typical copper zone, so that the unusually wide divergence, in point of time, between the igneous rock intrusion and the vein invasion, constitutes a

very marked exception to the more general rule. But in this case there is near-by evidence of my earlier suggestion (p. 362) that the ore deposition was genetically linked closely, not to the intrusive body with which it is found intimately associated, but to a later intrusion: for not far away are other dikes and necks of rhyolitic porphyry which are immediately earlier than the metalliferous veins, which are associated with them, and which occur in fissures of little or no fault displacement; and elsewhere in the immediate vicinity are other dikes and necks of a rhyolite of a more siliceous nature, which is younger than all the veins. It was, therefore, the middle intrusion with which the copper-bearing veins in question are genetically connected, and their association with the much older volcanic neck is fortuitous and misleading. This example suggests a further criterion which may be availed of in regions of repeated intrusions—that metalliferous veins are not intimately, even if remotely, genetically associated with igneous intrusions from which they are separated by a considerable space of time, as especially indicated by intervening fault growth, but are most intimately related to those intrusions to which they are immediately subsequent, and this immediate subsequence may be demonstrated by the veins occurring in fissures of little or no displacement in such igneous rocks.

Another copper-zone exception to the rule is that cited at Tiro General, Mexico, in Chapter V, where in successive faults which have developed on the margin of a sagging porphyry intrusion, first a zinc vein, and, later, after further faulting, a copper vein, were formed. In discussing this in the last-named chapter and applying the sequence criterion to the ore occurrence, I noted that the fact of the higher-temperature copper deposition occurring after the lower-temperature zinc deposition signified a rising temperature in the interval, and that this rising temperature could not be ascribed to the porphyry intrusive on whose margin the veins occur, nor even to its roots in depth, since the sagging of this intrusive mass, as evidenced by the mar-

ginal faulting, showed the normal subsidence after eruption, due to contraction and the cessation of upward magmatic impulse; and I ascribed the rising temperature during this period to the influence of some near-by independent intrusion. The fault-interval criterion, which I have developed in the present chapter, results in the same conclusion; and both combine to show that the Tiro General veins are not very closely connected genetically with the igneous intrusive on whose margin they occur; but that their localization on this contact is, genetically speaking, fortuitous, and simply due to the existence of fissure openings, for the explained physical reasons, along this contact; while the later intrusion with which the metalliferous veins were really most closely connected does not enter into the visible picture at all, although a little further geological work in closely adjacent territory would very likely supply the missing observations. Both Tiro General and Tepezala, therefore, belong in a class which might perhaps be called false contact deposits, since they occur, for physical reasons, on genetically more or less foreign contacts.

Even when ore deposits occur on the contact of their genetically nearest related igneous intrusion, in fissures of little or no fault displacement, my experience is that they are there localized (rather than away from the contact), largely for mechanical reasons, due to the fact that the adjustments in the igneous mass have produced fissuring along the contact. Where the fissures and the subsequent metalliferous veins occur in the igneous rock as well as in the intruded rock, this explanation is incontrovertible, as is the case in the typical instances of Matehuala and Velardeña, to which I have repeatedly referred; and similar cases are abundant in the literature. In these cases, the marginal association plus the test of the fault-movement criterion indicates that the ores are intimately associated with the particular intrusion which they accompany and have followed.

As such close associations are followed further and

further into the depths, do the periods of igneous intrusion and of vein invasion tend to draw closer together, and are there instances where the ore deposition is subsequent to the igneous intrusion, but not to its consolidation: where it accompanied its consolidation? There are doubtless examples which favor this conclusion,[17] although I am not personally familiar with them; and it is these which have led to the theory that the marginal ores in such cases were due to residual solutions—residual ore magma, we may call it—disengaged from the cooling rock as it consolidated, and entering the intruded rock. These occurrences did not in the least warrant the extending of this theory to practically all cases where ore deposits with lime-silicate gangue occur as an alteration of limestone on the contact of igneous intrusions; for many of these, as we have seen, are ordinary vein deposits, or replacement deposits in limestone controlled by the usual fissuring, and at the requisite temperature for the formation of lime silicates.

The instance of copper ores which in my experience comes nearest the specifications for contemporaneity of consolidation of magma and marginal ore deposits are the copper deposits of the Jibosa mine, near Jimenez, Chihuahua, Mexico. The other copper deposits of this "contact-metamorphic" type which I have seen and studied—namely, those at Matehuala, Velardeña, Bonanza, Mazapil, and Descubridora, in Mexico, and Helvetia, in Arizona, show the development of lime silicates and ore in the intrusive granite or monzonite as well as the intruded limestones and shales. At Jibosa, however, the case is different, in that the intrusive granite seemed on first investigation to contain no lime silicates or metallic sulphides. The lime silicates, which consist largely of garnet, of the dark iron-bearing variety with which the metallic sulphides are invariably

[17] See, on p. 583, the description of molybdenite ores in Canada; and on p. 568 the description of the platinum and chromium ores of the Urals. Both these represent deeper and higher-temperature zones of deposition than the copper horizon.

most closely associated in all the deposits of this kind which I have studied, occur as an alteration of limestone at the very contact of the granite, and the ore occurs in a few isolated shoots, also on the very contact, and in the dark garnet gangue. The granite is a moderate-grained biotite granite, frequently coarsely porphyritic; and contains dikes of finer porphyritic granite rocks, representing variations of the granitic magma, and pegmatitic portions inclosing veinlets or nests of magmatic quartz. It, therefore, shows many of the phenomena of differentiation, and upon my first examination I felt that here was at last a case where the lime silicates and the ore were due to solutions expressed from the cooling granite. The granite as exposed forms a horseshoe-shaped embayment, a mile or two across, in limestones and shales, the open side of the horseshoe being covered by the sands and gravels of the Mexican desert (Fig. 71).

Nevertheless, a further consideration of the field relationships finally excluded the hypothesis that the lime silicates and ores were the result of the action of solutions expelled from the igneous rocks at the levels now exposed by erosion. The dark garnet contact rock does not follow the whole contact, but is characteristic of certain portions, being especially well marked in local bays in the granite contact. In many places, the granite and the limestone come together, with the development of no garnets or other lime silicates whatever. This of itself negatives the theory that the solutions which deposited the dark garnet rock came from the crystallization of the adjacent granite, for if so there would be some garnet formed all along the granite rim; and it shows that this garnetizing action was due to solutions rising along the contact, containing silica and iron, and at or above the temperature necessary for the formation of lime silicates (see p. 262). As development of the ore by mining was carried on, in the few local shoots or chimneys on the contact which constituted copper ore, and the primary or sulphide ore was reached, it was found that the metallic sulphides—

pyrite and cupriferous pyrite—were subsequent to the lime silicates, and occurred in a gangue of fluorite and quartz, quite similar to the association and relation at Matehuala and Velardeña, and were, therefore, formed at a lower temperature than the earlier green garnet rock, or below the

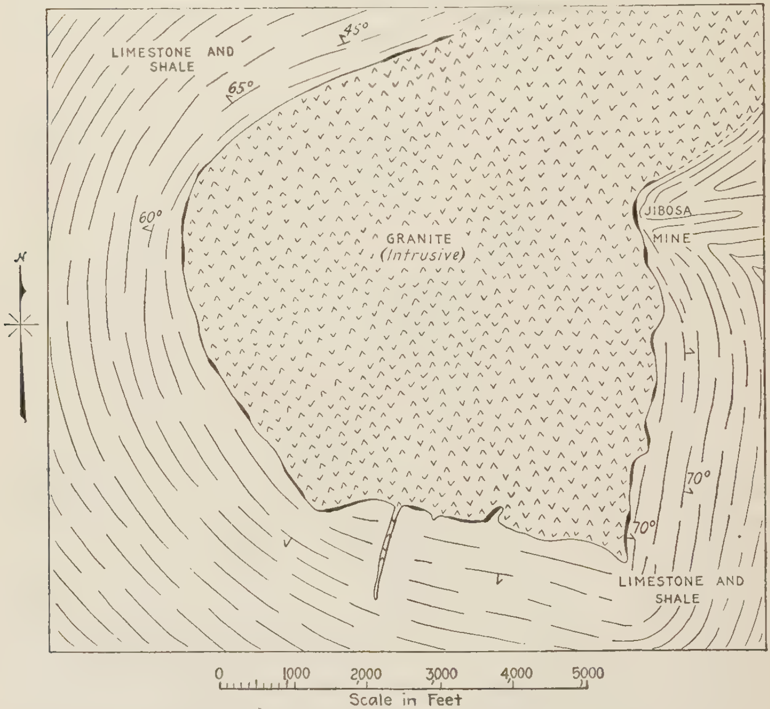


FIG. 71.—Jibosa mine and vicinity, Jimenez, Chihuahua, Mexico. Geologic sketch-plan, showing granite intrusive into Mesozoic limestones and shales. Sedimentary rocks dip away from intrusive plug or neck, showing forcible shoving up and aside by the latter. Deposits of specular iron, and, especially at the Jibosa mine, cupriferous pyrite, are at the very contact (shown in heavy black). See text.

critical temperature of the formation of lime silicates. Therefore, there was a decided time interval in this case also, first between the consolidation of the granite intrusive, and the dark-green garnet deposition, which immediately preceded the ore deposition, and another interval between the garnet deposition and that of the ore. Both garnet,

and subsequent sulphides, with their quartz-fluorite gangue, were deposited from solutions ascending from some greater depth, along certain shoots or chimneys of the contact. Deposition, therefore, obeys in general the same laws at Jibosa as elsewhere, in my experience. The oreshoots are localized on the contacts for mechanical reasons; and their deposition has depended largely upon the easy solubility and replaceability of the limestone. Examination of the underground workings at Jibosa showed that where a shelf or tongue of the granite crossed the path of an oreshoot at the contact, then in this case the primary ore had replaced the granite also; and in the granite the dynamic record is clearer than in the limestone, and shows that the granite had been shattered and broken to afford channels for the ore-bearing solutions.

Therefore I have finally to remark that I have never seen a case of copper ore deposition along a granitic (or monzonitic, or dioritic) contact where the ore was not subsequent not only to the intrusion but to its consolidation; and (as the consideration of the Jibosa case, as one showing apparently the least time interval between intrusion and ore deposition, will show) decidedly subsequent to the consolidation, and with a marked time interval. And this tends to confirm me in my conclusion that the ore magma is not the residual fluid which is expelled from igneous rocks of the middle and upper zones—from the porphyritic intrusive rocks and the superficial denser intrusive and extrusive lavas—by the relatively rapid crystallization forced upon them by the migration from a hotter zone below to a cooler zone above, but is a special magma developed at the specially favorable and certainly relatively deep zone where there takes place the rock differentiation which we geologists all recognize as surely existing, like the existence of the electric forces, but cannot yet clearly understand, any more than we can these electric forces.

One of the forms of current advanced thought is that the ore magma is so formed, at the moment of crystallization

of igneous rock at any depth: that we can actually see such a magma at the surface, in the clouds of aqueous and other vapors which are given off from surface lavas when cooling, and which contain, besides their gaseous constituents, sulphur, boric acid, sodium chloride and sulphate, ammonium chloride, potash alum, and other salts, with small quantities of practically all the metals. There is no denying the diagnostic value of these volcanic emanations, and the wonderful insight they give us into the nature and composition of an igneous magma. They have not been studied half enough, or considered half enough. It is from this actually observed phenomenon that we have learned what otherwise we would possibly never have clearly seen: that magmas which consolidate in depth must first free themselves from this abundant water, carbonic acid, nitrogen, sulphur dioxide, and other gaseous magma constituents; and that these carry with them in greater or less degree various earthy or metallic salts.

It was a natural step in our explanation of ore deposits to assume that this constituted the typical ore magma, and it has been commonly held so by many, including myself, as I have gone on record in various publications to which I will not now take the time and space to refer. Even after clearly perceiving that the typical ore magma, for the plutonic ore deposits, was a magmatic differentiate manufactured in that same relatively deep zone or hearth where were segregated from the mother magma the various rock types which have sprung from differentiation, I have not hitherto been able in my own mind to overcome with this observation and deduction from the depths (derived from study of those deep plutonic rock and ore phenomena like the occurrences at Silver Peak, in Nevada, now exposed by deep erosion), the other line of observation and deduction at the surface, based on volcanic manifestations; and I, therefore, in my own mind, tried to harmonize the two sets of phenomena, and while acknowledging the differentiation process as the true explanation for ore magma, I have been

inclined to regard the volcanic emanations as analogous, and, therefore, due to a forced differentiation process, effecting suddenly (through the accident of the mother magma or lava having been hurled into a cooler zone) the separation, from the materials which were to make up the solid rock, of the volatile and easily volatilized elements; and that this residue was really the ore magma which I had deduced for the plutonic depths, but which in these depths took place with the almost unlimited leisure of a vastly slow process of coagulation and crystallization.

The deposits of the compounds of the rarer metals around volcanic fumaroles make this reconciliation of ideas plausible, since this deposition shows that these expelled gaseous elements of the lava magma have been scavengers or collectors of the metals from the magma, or at least their associates. True, these metallic deposits from volcanic emanations are scanty and rare, and of only scientific, never commercial, interest; but the non-metallic deposits from volcanic emanations, like sulphur, boric acid, and other materials, do become of important economic interest and, therefore, become ore deposits.

With this conception in mind, and reasoning accurately that a similar relatively sudden separation of the volatile elements of the magma upon its cooling into rock would take place in the intermediate depths, after intrusion of what we now may study as, let us say, a porphyry or porphyritic igneous rock, the analogy between ore deposits associated with these intermediate intrusives and the rare metallic compounds deposited from volcanic emanations has led almost inevitably to the conclusion that these ores of the intermediate depths were deposited from that volatile portion of the magma expelled at the time of consolidation; and the so frequent occurrence of ore deposits on igneous contacts is apparently strongly in line with such a theoretical conclusion, if we do not examine these marginal ores too closely. But it will be remarked that neither the surface lavas nor these intermediately cooled magmas show any

signs of differentiation other than this forced differentiation of the gases—they show no signs of differentiation, producing various allied or consanguineous types of cooled rocks, such as we find to have been produced by magma differentiation at the favorable very deep zone, and the proof of this segregation is closely tied up with the proofs of the closely allied segregation of the ore magma in the same zone. In other words, our proofs of the origin of the ore magma by magmatic segregation lie in the recognition, in rocks representing the extreme depths opened to us by erosion, of the gradual transition of one type of igneous rock to another, of granites and other rocks to pegmatites, of pegmatites to quartz veins, with or without metals, and of the gradual and orderly sequence of the different metals in these plainly magma-derived quartz veins.

All this, as we may observe and study in any district where the phenomena, or rather the frozen stages, of magmatic differentiation are exposed to our view, has taken a relatively vast amount of time; and we may clearly see in these districts that without that extended time the process of differentiation, the segregation of a pegmatite magma with feldspathic pegmatites and quartz veins, could not have taken place, nor the segregation of the specialized ore-magma solutions rich in the metallic constituents. Pegmatites are not essentially ore-bearing: but their occasional metallic constituents offer a diagnostic clew, like those of the exhalations of surface lavas. A stage of leisurely differentiation further than the pegmatite stage or in some magmas a distinct and leisurely operation[18] has been necessary to concentrate the typical ore magmas which have deposited those important plutonic ore deposits whose origin we seek.

I am, therefore, forced to the conclusion that neither the

[18] As is the case with the chromite-platinum deposits of the Urals, which do not necessarily originate through the transitional pegmatite stage, but form metallic concentrations direct from the rock magma. This is particularly true of the basic rock magmas.

surface exhalations, nor the corresponding expelled volatile and aqueous residue which undoubtedly is disengaged from the intrusive rock at intermediate depths on consolidation, constitutes or represents the magma from which important metallic ore deposits, in the broad sense, are formed.

A further evidence of this my last conclusion stated above is obtained from the consideration of those ore deposits associated with intrusive rocks of the intermediate depths, which show the closest relationship to the igneous rocks and their contacts—namely, the copper deposits. If, as has been currently considered, they represent the metallic constituents expelled from the magma by the consolidation of the immediately associated rock, why are they typically copper deposits? Why are not the other metallic zones which have been worked out for plutonic ore deposits, and which have been sketched out in the preceding chapters, equally represented? We should have, indeed, on the current theory, a complex mixture of metals deposited on these contacts, including gold, tin, tungsten, copper, lead, zinc, and silver.

The response will be made to this my criticism that "contact" deposits containing most of these metals in commercial quantity are found here and there: by this is meant ores carrying these metals in a lime-silicate gangue, on the contact of or near an igneous intrusion. This is a broad subject, and I will not discuss it now, except to warn my readers against hurriedly arriving at any possibly false classification from the occurrence of any group of metals in connection with lime silicates and igneous intrusives, for the metallic deposition in the cases I have studied is almost always separated by a marked time interval from the igneous rock intrusion, and generally by a considerable time interval from the lime-silicate deposition. I will simply remind them that the rule holds, that by far the most usual ore deposit found under these conditions is of copper—copper-bearing pyrite and chalcopyrite; and this general

rule of itself renders untenable the current theory of derivation from the magma represented by the immediately adjacent igneous rock. It harmonizes with the observations which I have given above, to the effect that the copper ores, in my experience, are always distinctly subsequent to the rock consolidation, and demonstrates that these copper deposits have a plutonic origin, and that they are derived from a deeper source than the horizon in which they occur. We must, indeed, look lower down; and in acknowledging the deep-seated or plutonic source of these copper deposits along igneous contacts, we must recognize the existence of still deeper zones of metal deposition, such as the gold zone and the tungsten zone, between the copper zone and the starting point of the ore magma, so that the source of this magma must be many thousands of feet deeper than the zone of copper deposits as we find them, instead of being in the zone of the adjacent or neighboring igneous rock now exposed.

This conviction induces us, in our search for the source, to abandon these copper deposits as a possibility of most direct evidence, and to transfer our investigation to those regions where not only the copper stage of deposition but lower zones are shown, as the gold veins of California, which are older than the copper deposits which lie in the same region, or the gold veins of the Appalachians, which have the same relation to copper veins, or to that sequence of gold veins and copper veins which I have described (Chapter II) in Manitoba. The two regions last named will be especially illuminating, for there it can be shown that the gold veins are traceable back in the sequence, approaching the point of origin, to pegmatites showing a still deeper metal zone, such as the molybdenite of Crowduck Bay, in Manitoba (Chapter II, p. 100); and the further tracing back of the genealogy of the ore magmas leads us to the plutonic granites themselves. Where the pegmatite dikes are later than the granite, we must look still deeper for the actual zone where the differentiation has taken place: but there

are places where the gradual transition of granite to pegmatite may be observed, with no time interval between: the pegmatite, instead of being an intrusion, forms nests or segregations in the granite, and there is an unbroken crystallization between the latter and the former, although the coarsening of crystallization between the two is rapid.

This coarse crystallization of the pegmatitic nests, as discussed in a previous chapter, is clearly due to the presence of a greatly increased amount of water and other volatile magmatic constituents in certain nests or pockets or small reservoirs, as the granite crystallizes; and we have, therefore, the proof that we have arrived at the locus of the genesis of at least one type of ore magma, and that the processes of its segregation are in some instances laid open by deep erosion for our study. The pegmatites themselves, of course, even when ore-bearing, do not represent, in these many nests and segregations, more than a fraction of the magma which has been gathered together from the granite; to visualize quantitatively the whole ore magma thus concentrated, we shall have to consider the further fractions, which crystallized higher up as the ores of gold, copper, lead, zinc, silver, etc., with accompanying gangues of quartz, fluorite, and other earthy minerals; and we shall also have to consider the aqueous and other volatile ore-magma constituents which we know to have been in solution with these now solid minerals, and which escaped as a final never-crystallized fraction of the ore magma.

The relationship and yet the difference between volcanic emanations at the surface, and segregations from a vastly slow-cooling magma of the deep-seated or plutonic type, is thus seen. The formation of the ore magma in depth will be with great leisure; for the zone fitted for its complete development, and therefore where it will take place, will be that magma zone immediately overlying the permanently stable magma, which zone I have, therefore, called the zone of differentiation. Here ample time and opportunity are often offered for the separation of an aqueous-

gaseous magma from the crystallizing rock, including the separation and transportation of the metallic ore-magma ingredients; and, moreover, for the segregation and collection of those earthy constituents which are superfluous in the more or less eutectic mixture of the rock which is forming from the rock magma. Thus the first stage of the pegmatitic magma is formed, and time and opportunity are afforded for the drawing together of this magma from many points.

But the conditions favorable for slow collecting together of elements according to chemical affinities still exist, and allow a further differentiation. They allow the first pegmatitic magma to effect a second segregation (by the repetition of the first process) of the aqueous-gaseous constituents, resulting in a relatively dry or aplitic magma, which crystallizes as aplites, and a more highly pegmatitic magma, richer in the metals, which does not crystallize, as a matter of field observation, with the aplite stage. Still further, from this more highly pegmatitic or superpegmatitic magma, the available time is sufficient for the crystallization of the pegmatites, with or without metallic constituents; for the crystallization of the quartz veins at the requisite lesser temperatures, with their accompanying characteristic metallic minerals at stated zones or temperatures; and even for the splitting up at any stage and under appropriate temperature conditions into sub-magmas wherein the earthy materials and the metallic substances may part company, and each may migrate independently and crystallize separately, just as we find them in nature. This perfect development and final differentiation of the pegmatitic magma (which is the first stage of most ore magmas, although a stage which appears to be inconspicuous in the very basic magmas), and of the more highly specialized vein and ore magmas, I may repeat, plainly depends on those conditions of very slow cooling and consolidation which are fully developed only in the nearly stagnant magmas of the plutonic rocks, at the lowest

depths where incipient consolidation supervenes; and takes time for the repeated fractional splittings—even though the final injection and crystallization of some of the end products as mineral veins may take place at a single geologic episode: much as any rock magma, similarly differentiated at leisure from the other rock magmas, may be suddenly injected upward and cooled.

At the opposite extreme to the conditions of the deep-lying zone of differentiation are the conditions under which the surface volcanic emanations are separated from the cooling lavas, suddenly and without opportunity to gather together in quiet basins or nests for further differentiation. The aqueous-gaseous residue expelled from an intrusive rock at the intermediate depths is, of course, analogous, and similarly incapable of segregation so as to form the important concentrations of metallic minerals which we commonly call ore deposits.

The term "ore deposit" is, of course, relative, for metals occur in all rocks and even in the sea; but what we recognize as ore deposits, which are unusual concentrations, valuable commercially, are probably formed, for the rarer metals, such as gold, silver, copper, lead, zinc, tin, tungsten, molybdenum, nickel, cobalt, antimony, arsenic, and the like, typically even if not exclusively by the slow plutonic process of magma differentiation above sketched. The suddenly expressed juices of the volcanic and intermediate intrusive rocks are not distantly related to, though by far not identical with, the first pegmatite magma of the depths, and may carry in solution both earthy and metallic magma constituents; but, since they have no opportunity to further separate their constituents, and to form highly specialized ore magmas, it is probable that they do not form workable orebodies of the class of metals above enumerated, or indeed of any metals. The workable deposits of boric acid, sodium chloride, sodium sulphate, and alum which they do form, on the other hand, are not formed in plutonic deposits or plutonically derived deposits, since boric acid,

the alkaline chlorides and sulphates, and the like are probably contained in the final fraction of the superpegmatitic or pegmatitic ore magma, which fraction is not precipitated in the lower or intermediate, or indeed the superficial, depths, but is brought clear up to the surface by residual magmatic hot waters. The element which more than anything else indicates the analogous derivation of volcanic emanations and ore magmas is the sulphur. Cooling lavas give off immense quantities of sulphur, and native sulphur, deposited around volcanic fumaroles, forms commercially valuable deposits. In the plutonic residual magma, the presence of much sulphur is shown by the ordinary deposition of the metals as sulphides, and especially in the great deposits of pyrite which are frequently formed at intermediate depths, from the plutonic ore magmas.[19]

It may finally be recapitulated that the ripe ore magma, separated from the very slowly cooling plutonic rocks and often accumulated in domes in the plutonic igneous roof, avails itself of the first subsequent fissuring of the overlying solid rocks to ascend and form mineral veins: and that such fissuring is oftenest due to readjustments caused by the shiftings in igneous masses. When it is the adjustments of the underlying plutonic mass itself which cause the cracking of the roof rocks, the ascending ore magma may form veins in the intermediate and upper zones with no visible close association with igneous intrusions. Where, however, an igneous magma has ascended by intrusion into the intermediate and upper rock zones, the adjustments of this magma on consolidation invariably create fissures in itself and the adjacent intruded rocks, and such fissures are more apt to be concentrated along and near the igneous contact than elsewhere; and the ore magma avails itself of these fissures to rise and crystallize as successive ore zones, if there is any available reservoir of such magma which the new system of fissures can tap; and in that case we have ore deposits immediately subsequent to intrusions

[19] For an extension of this discussion see Chapter XI.

of the middle and upper depths, and with noticeable frequency along their contacts. Where all these conditions are not present, no ore deposition immediately subsequent to a given intrusion will occur. The lack of such marginal ore deposits on most intrusive contacts shows that the local residual solutions are not, *per se,* ore magmas. At some subsequent date, however, through all the vast succeeding period of geologic time, an extension of the fissuring may tap an ore-magma dome or basin in the plutonic depths, and this ore magma may rise and crystallize, and so form ore deposits in the igneous rock, in the fissures along its contacts, or in the intruded rocks, which ore deposits, therefore, appear at first sight to be closely related genetically to an igneous rock with which they may have only a fortuitous physical connection, forming frequently, therefore, what I have called false contact deposits (p. 369).

It may further be summarized that in general the relation of most ore deposits to associated igneous rocks has a physical explanation resting chiefly on the formation of fissures,[20] even in those normal cases where the veins have followed directly upon the intrusion; and that the distant genetic association of intrusion and ore becomes more and more intimate with increasing depth, when both rock and ore approach nearer their initial point or zone of departure, and becomes recognizable with confidence only in the plutonic zone. Even in this plutonic zone false associations, due to entirely physical causes, are very frequent, and are deceptive except on close study: for example, in the case of plutonic gold-quartz veins, which may occur near or on the contact of basic (diabase) dikes, which are one of the results of rock differentiation, whereas they are really genetically related not to these, but to the alaskitic and pegmatitic dikes which are complementary to the diabase as rock-differentiation products. I have noted this in the case of Silver Peak, in Nevada (p. 90), in Alaska, and very many other places. Such complementary basic

[20] And on the heat of the cooling igneous rocks (see p. 834).

and siliceous intrusives may cause similar confusion in higher ore zones, as for example in the copper-bearing district of Miami, in Arizona, where Ransome inferred a genetic relationship of the ore deposits to a diabase intrusion, whereas his mapping indicated a closer relation of the ores to a granite intrusion. Across a mountain range from Miami, similar ores and intrusions occur in the Ray copper district, and I pointed out here that the most intimate genetic relationship of the ores was to a granite intrusion, and that the close physical association of some of the ores with intrusive diabase was deceptive; and Ransome subsequently came to the same conclusion for this district.

CHAPTER IX

Epochs of Ore Deposition

This chapter points out that ore deposits are characteristic of certain brief and widely separated geologic epochs only, called by De Launay metallogenetic epochs. Such epochs occurred in the Paleozoic and the Mesozoic on the present Atlantic and Pacific coasts; in the Rocky Mountain region, and further west (also probably further east), in the post-Cretaceous and Tertiary. The post-Cretaceous-Tertiary belt of ore deposition rims the entire Pacific Ocean.

It is pointed out that as metallogenetic epochs are dated back to more and more remote geologic times they will characteristically show deeper and deeper zones of ore deposition, and hence different characteristic metals, on account of relative erosion.

Arizona is cited as a wonderful example of copper concentration, in which metallogenetic epochs resulting especially in much copper deposition took place at least four times—in the pre-Cambrian, Permian, post-Cretaceous, and later Tertiary. Arizona, therefore, illustrates and forms a metallographic province.

THE FACT that ore deposits are characteristic of certain geologic epochs only, and that between such epochs there has been no ore deposition, has been been recognized pretty widely of late years, and has been brought forward by various authors, notably De Launay in France and Lindgren and myself in the United States; and I shall touch on it only briefly and connect up these well-established facts with the principles I have discussed in preceding chapters, confining myself mainly to the Cordilleran region of North America. In speaking of ore deposits in this chapter, I shall refer to the most important group of deposits of the rarer metals which I have discussed exclusively hitherto in this book—the igneous-magma ore deposits.

Any one who has pondered over the occurrence of ore

deposits in our Western states cannot fail to have been struck with the fact that ore deposition has occurred at distinct epochs, in each of which it has taken place in a very brief space of geologic time; and that between the periods of ore deposition have elapsed immense stretches of time, covering many millions of years, during which no metalliferous veins were formed, although all through these aeons, over a period of time so great that it is beyond our conception, all the uniformitarian processes of geology, like erosion and sedimentation, went steadily on. This consideration of and by itself disposes once and for all of any theory that refers ore deposition as a whole or in general to processes which must always accompany erosion and sedimentation, such as circulating ground waters of atmospheric origin, whether cold or warm, ascending or descending, shallow or deeper-seated; and, incidentally, it disposes of the theory that the metals which have been concentrated into commercial ore deposits were leached from minute quantities disseminated in rocks by the agencies in question. If there are exceptions to this unquestionable, definite, and decided rule, they will not militate against the clarity of it. I shall discuss such exceptions more or less systematically in a succeeding chapter; but here I will state that for a given important ore deposit of the rarer metals like copper, lead, zinc, tin, tungsten, gold, silver, antimony, and the like, the chances are at least a hundred to one, before or after examination of its relations, that it belongs in the class which has its advent only once in a vast period of time. For out of those orebodies which have been studied in our Western states, nearly all plainly fall into these narrowly defined geochronological classes; and studies outside of this region demonstrate that the laws worked out here are not peculiar to the region, but are in general of worldwide application.

Another fact has also been well established within the period of my own geological experience—that is to say, in the last thirty years or so: namely, that the critical periods

of widespread ore deposition were also periods of igneous intrusion, and that the two phenomena have been closely associated. The periods of igneous intrusion have proved after comparative geologic research to be also separated by enormous time intervals, during which the processes of erosion and sedimentation, and the change of climates, went on without interruption. With igneous intrusion and ore deposition, at these critical periods, is associated also a third occasional geologic phenomenon, which does not fall into the class of uniformitarian phenomena such as erosion, weathering, and underground water circulation—namely, rock deformation, or folding and faulting of rocks, due to their being shoved into a narrower horizontal space, or uplifted, or being stretched to compensate for a compression somewhere else. The recognition of the frequently close association of periods of igneous intrusion and periods of rock deformation is of long standing, and antedated the recognized connection between intrusion and ore deposition. But, to my notion, the cart has usually been put before the horse, and the deformation considered to have been the cause of intrusion, by providing fissures, or by squeezing magma bodies up into the crust or out on the surface. I have in an earlier chapter (Chapter IV) discussed my belief that most rock deformation results from various movements of magma.

Deformation and intrusion are not so intimately associated, either areally or chronologically, as are intrusion and ore deposition. Such a dynamic stress as is instituted by a thrust from any source, as from a moving magma, is taken up by adjustments in the rock over considerable distances; and such adjustments, if expressed in folding and faulting, may precede the arrival, at any given locality, of the magma, and may continue long after its advent, on account of magma movements due to change of bulk on consolidation.

The acts of igneous intrusion (including volcanic activity), ore deposition, and marked folding and faulting,

are occasional, even rare, geologic phenomena, and are interrelated; and so are to be distinguished in a way as catastrophic, precipitated only by rare circumstances, as contrasted with the superficial processes of geology, which depend upon the reaction of rocks with atmosphere.

When we come to define the chief periods of catastrophic activity it is the same with this quest as with all others in geology—we must really confine ourselves to the geologic column from the Cambrian down to the present, for earlier than this the geologic events of the inconceivably long antecedent period of time are obscured or obliterated. We know that life on the earth, and the long-drawn-out march of geologic events, went on long before the Cambrian, but elucidation of the blurred remaining records is slow and difficult. Therefore, when we say that the earliest period of ore deposition in the Western United States was pre-Cambrian, we know that we may or must be classifying various periods as one. A fact of real interest, however, is that these pre-Cambrian ore deposits are associated with igneous intrusions in precisely the same way as are the post-Cambrian ores, proving a similarity of governing laws, so far as we know, throughout all geologic time. The discussion of pre-Cambrian ores and the evidence of their having occurred at wide-spaced intervals of time, in connection with widely separated igneous intrusions, is an interesting study; but my only object in this volume is to discuss a few of the simplest principles governing ore deposition, and the object of this chapter will best be accomplished by referring only to the geological record which is almost everywhere legible—that of the post-Cambrian rocks.

In North America, the Appalachian belt was the earliest site of post-Cambrian folding, intrusion, and ore deposition, and in the Paleozoic all these went on; the ores of this general period belong partly to the pegmatitic type, and include a little tin, molybdenum, graphite, monazite, etc.; also, they belong to the deep-seated gold-quartz veins; and,

finally, they include copper pyrite ores, and pyrite and pyrrhotite ores poor or lacking in copper. Lead ores are scarce and mainly not of commercial value. During this period of disturbance and intrusion in the Appalachian belt, the crust from the Appalachians nearly to the present Pacific Coast remained in comparative quiet and free from folding, intrusion, and accompanying ore deposition; and the sedimentary rocks were laid down upon one another in the ocean, age after age, with little marked disturbance or deviation from the horizontal position. Thus, Cambrian, Silurian, Devonian, and Carboniferous followed one another. In the great area which we now call the Middle States, the relatively slightly disturbed horizontal position of the rocks has lasted till the present day. This statement is, of course, relative, for we do find in these rocks broad anticlinal domes and synclinal basins, very important in the genesis of the petroleum deposits which occur in that region; and there are also faults and occasional dikes, as well as important ore deposits. But not till we get as far west as the Rockies do we find the strata sharply folded, with numerous and large igneous intrusions; so that there is a sharp line, in this respect, between the bold east front of the Rockies in Colorado and all that country lying between that range and the Appalachians.

As an example of the crustal history in one arbitrarily selected spot in the Rocky Mountains, I will summarize, with apologies, the sedimentation in Aspen, in Colorado, a district oft quoted, because it happens to be familiar to me. At the base of the geologic column in Aspen are the pre-Cambrian granites and schists, which represent an island in the Cambrian ocean. The earliest feature of the record at Aspen shows that this granite and gneiss was much disintegrated near the surface, and therefore formed part of a flat-lying land, which subsided beneath the ocean in the latter part of the Cambrian era. A thin bed of gravel (now conglomerate) followed by fine white sand (now quartzite), shows a gradually subsiding crust and a deepening sea;

still later the sand became mixed with lime detritus (now dolomitic quartzite), showing a still further subsidence; then came sands containing glauconite, showing deposition intermediate between the zone of active deposition of eroded land materials and of the limestone deposition of the outer seas; then a gradual transition to lime sediments (now siliceous dolomites) which carry (lower) Silurian fossils. This thin series of beds, only 200 to 400 feet thick, thus records a tranquil subsidence, bridging the later Cambrian to the Silurian, and the slow deposition, in an ocean, of sediment from a flat, sinking continental island. In the Silurian, some 250 to 300 feet of limestone was deposited, under static and uniform conditions. Subsequently, at some period in the later Silurian, a sudden but uniform and widespread elevation took place, and the formations above described were transformed to dry land. Sand from the limestones which had thus emerged, mingled with sand from the old central area of granite and gneiss, next accumulated as a thin but widespread mantle, and this sand was mixed with a fine lime precipitate indicating deposition in shallow land-locked waters. Devonian fishes lived in these shallow waters. These sediments are only 60 feet thick at Aspen and about 40 feet thick at Leadville, where the deposit was more of a clean sand (now called Parting quartzite): and in the Kanab valley, in southern Utah and northern Arizona, 300 miles from Aspen, they vary from 10 to 100 feet in thickness. It may be imagined how flat the surface must have been during all this vast period to have enabled such a thin series of sediments to be so continuous and widespread. So far, certainly, since the early Cambrian, no rock disturbance—only a very slow subsidence, and a more rapid upheaval, but only sufficient to just raise the rocks above water.

In the early Carboniferous the crust subsided again as rapidly as it had risen in the late Silurian, and limestone sediments again formed. After some 250 feet of this limestone was deposited, it was altered to dolomite by the

magnesium salts of the shallow evaporating sea or great landlocked lake in which it was deposited; but later subsidence connected the lake with the open sea, and lime sediments were deposited which did not become dolomite. These sediments are 100 to 150 feet thick, and accumulated in comparatively deep water.

At the close of this deposition another great upheaval took place, so that these rocks became dry land. At a later period the movement was reversed, and subsidence took place, so that water again covered the Aspen district. In these waters new sediments were laid down in upper Carboniferous (Permian) times. Although no folding had accompanied the last uplift, it was evidently sufficiently great to form, for the first time since the pre-Cambrian, a bold land mass, which erosion attacked vigorously; for even during the subsequent subsidence, the sediments, deposited in shallow seas near the land, were formed at a rapid rate.

The first sediments consisted of materials worn chiefly from the pre-existing sedimentary beds, mainly limestones and dolomites, and the material contained much carbonaceous matter derived from the land plants, which locally formed thin beds of impure coal. Later the older sedimentary beds were in some regions entirely stripped off from the land, exposing again the underlying pre-Cambrian granite and gneisses, and these were eroded with the same speed, forming thick, dark-red sands (sandstones) whose color alone shows very rapid deposition. The limy, shaly, and dolomitic beds deposited before the sands began were about 1,000 feet thick, while the sands later on deposited, still in the Permian period, were around 4,000 feet thick. These sands became purer as the close of the Permian period came on, and in the period known as Triassic; and in this last period some 2,600 feet of sandstones were deposited. During all this time, the land was sinking, as is proved not only by the character of sediments but by the overlapping of the red Triassic sandstones upon the old granite island. A considerable uplift subsequently

transformed this region to one of shallow fresh-water lakes, in which sedimentation went on slowly in the Jurassic, showing that the high Permian-Triassic mountains had at length been worn down. These sediments were fine-grained sands and muds (now sandstone and shale), and are only about 300 feet thick.

A subsidence followed, and in the early Cretaceous period white sands to the extent of some 250 feet were deposited, not only here but over a wide area; that these were still deposited in a great inclosed sea is indicated by the plant remains in their upper parts. A further subsidence let in the open sea, and sediments with marine fossils were deposited—first 350 feet of lime mud (now calcareous shales), next 100 feet of limestone, and then 4,000 feet of muds, more or less limy (now shales with black limestone layers). These muds were deposited in comparatively still waters, not very close to land, and were derived from a land surface that was being actively but quietly eroded. Above these thick muds was deposited 100 feet of white sands, indicating an immediately preceding uplift, and then came a considerable thickness of sands with plant remains, and elsewhere important coal seams. The beds of sandstone become more important in comparison with the shales in the upper portion, indicating a growing spasmodic uplift which is further shown by the transition from marine fossils to fresh-water fossils again, the geochronological period of this transition being in the late Cretaceous.

Upon this last growing uplift we must now fix our attention, for while the many repeated uplifts during the long geologic ages had each foretold nothing more strenuous than a succeeding subsidence, this particular late Cretaceous uplift was a forerunner of catastrophic geologic events which the region of what is now Colorado and vicinity had not experienced since before the beginning of the Cambrian. The general uplift raised above the Cretaceous ocean the whole mass of the present Rocky Mountains in Colorado; and beneath this area great masses of molten

rock gathered, and at frequent intervals thrust themselves upward into all the sedimentary rocks which had accumulated one above the other since the beginning of the Cambrian: as dikes, narrow or wide; sheets or sills of all degrees of thickness, caused by the lava intruding between the sedimentary beds; laccoliths or blister-like accumulations of lava between sedimentary beds, of such size that when stripped by erosion as at the present day, in some cases, they become mountains; as large irregular masses; and probably as surface flows. All the sedimentary rocks were violently contorted by folding at this time, and by faulting, a thing which, like the intrusion of molten igneous rock, had not happened since before Cambrian times. The main folding and the igneous intrusion were closely related in point of time, for (to depart a little from the Aspen district, to piece out our history) the existing sedimentary rocks of later age—the Tertiary strata in Colorado—were laid down upon the upturned and eroded edges of the Cretaceous beds, thus signalizing the great unconformity between these two periods—the greatest unconformity, in this region, of the whole recorded geologic column. The Tertiary beds themselves are not undisturbed and horizontal, but show folding and faulting, indicating a continual or recurrent disturbance and readjustment in the rocks throughout the Tertiary and down to the present day; and throughout all but the latest part of this period—the very late Tertiary and the Pleistocene—intrusions and surface flows of molten lava repeatedly took place.

With these intrusions, and with the folding and faulting of the rocks, was also associated the deposition of ore and the formation of mineral veins, which occurred at repeated sharp periods, punctuating geologic history, as did the igneous intrusions; while the rock adjustments, although, as above noted, most violent at the first great period of intrusion and ore deposition, yet bridged the divers igneous-metallogenetic periods and persisted beyond them down to the present day. In a rough way the igneous intrusions and

the accompanying ore deposits may be divided into two general periods, the first of which was marked by intrusions of chemically intermediate or monzonitic magma lasting from the earliest to the middle or later Tertiary, and the second of which was signalized by the outburst at isolated volcanic centers of varied magmas which have an alkaline (phonolitic) tendency.[1] The principal metals of the ore deposits are silver, gold, lead, and zinc. Nearly all of them are associated with intrusive rocks and represent the intermediate and upper regular zones of ore deposition—the auriferous pyrite zone (exemplified by portions of Leadville and at Idaho Springs), the zinc zone (Leadville, Aspen, Georgetown, etc.), the lead zone (Leadville, Aspen, Georgetown, etc.), and the silver zone (Aspen, Georgetown, etc.). The copper zone is unimportant, but the minerals of the still deeper zones, such as tungsten and molybdenite, are locally strikingly exhibited, the former at Boulder and the latter at Climax.

In the whole stupendous range of geologic time, from the beginning of the Cambrian down to the present, therefore, there was, in the Colorado region, igneous intrusion, marked folding and faulting, and ore deposition during one geologic period only—the Tertiary, representing a very small fraction of the total lapse of time (Fig. 72).

Further west in this Cordilleran region, however, events were by no means always synchronous. In the present Pacific Coast region, including Alaska, there were igneous intrusions and volcanic outbursts from the early Paleozoic on; and in the Triassic period there were also copious igneous intrusions and extrusions, and these occur as far east as central Nevada.[2] Ore deposition, especially of copper, and certainly rock deformation, attended these earlier igneous movements, of which the record is much obscured.

[1] J. E. Spurr and G. H. Garrey: "Geology of the Georgetown Quadrangle, Colorado." *Professional Paper* 63, U. S. Geol. Surv., Washington, 1908, p. 129.

[2] J. E. Spurr: "Descriptive Geology South of the Fortieth Parallel." Bulletin 208, U. S. Geol. Surv., p. 101.

At the close of the Jurassic or the beginning of the Cretaceous, the Sierra Nevada region was intensely folded and uplifted, and the present mountain fault block which constitutes the main range was initiated by the development of the great fault which runs along its eastern base, and which has been the sliding plane for repeated uplifts of the block between that time and the present day. This Jurassic-Cretaceous period had an epochal geologic significance in this region like that which the Cretaceous-Tertiary period had in Colorado. Numerous intrusions—sheets, dikes, and batholiths—were pushed into the older sediments, and were of chemically intermediate or monzonitic (granodioritic) rocks. These intrusions took place nearly as far east as central Nevada and central Idaho, and were closely associated with folding and faulting. They were also closely associated with very important ore deposition, especially shown at the present day by deposits representing the relatively deep-seated zones of gold and copper, with some lead, zinc, and silver. The folding and faulting did not affect the greater part of the more eastern area—Utah and Colorado—which displays no igneous phenomena of these periods: although subject to relatively feverish elevation and depression, the rocks remained, as before, approximately horizontal. In fact, east of the Wasatch Mountains there is no especially strongly marked hiatus or disturbance recorded in the sediments as we pass through this Jurassic-Cretaceous critical period, which in the Pacific belt was accompanied by the greatest upheaval, folding, and faulting since the pre-Cambrian.

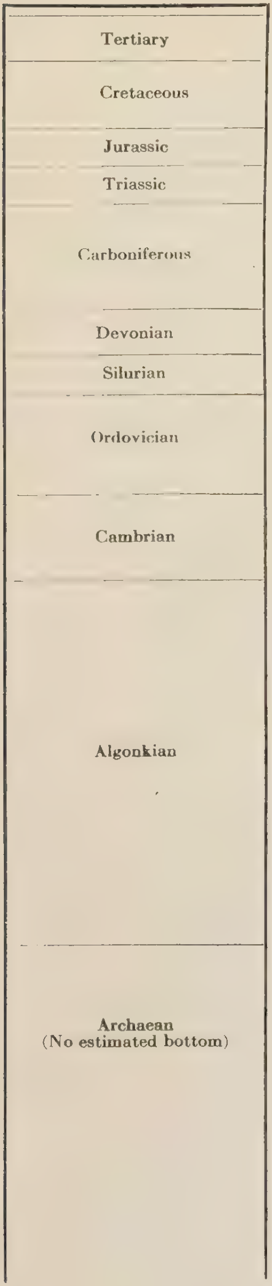
On the other hand, the phenomenal uplift which affected Colorado at the close of the Cretaceous, with attendant folding and ore deposition, does not appear to have affected California, for the upper Cretaceous and Tertiary strata which occur in the Sierra Nevada lie nearly or quite horizontal. Throughout the Tertiary, in Nevada, however, there was a recurrence of copious volcanic intrusions and extrusions, accompanied by folding, faulting, and ore depo-

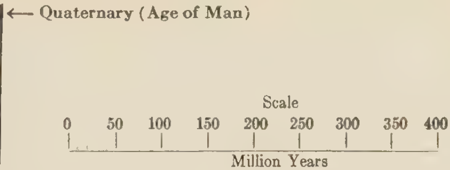
STANDARD TIME SCALE

(As arranged by George H. Ashley; Time Scale from Joseph Barrell)

ERAS	AGES		
CENOZOIC (Recent Life) Era of Mammals	QUATERNARY 1 Million yrs.		Age of Ice and Man
	TERTIARY 60 Million yrs.	Lower Upper	Age of Mammals Evolution of Primates Maximum thickness of strata, 40,000 feet
MESOZOIC (Middle Life) Era of Reptiles	CRETACEOUS 75 Million yrs.	Lower Upper	Culmination of Reptiles Maximum thickness of strata, 50,000 feet; thickness in Montana, 24,000 feet (lower Cretaceous only); thickness in California, 26,000 feet (upper Cretaceous only)
	JURASSIC 40 Million yrs.		Age of Reptiles Evolution of Birds Maximum thickness of strata, 18,000 feet—in California
	TRIASSIC 40 Million yrs.		Increase of Reptiles Evolution of Mammals Maximum thickness of strata, 20,000 to 30,000 feet, apparently—in Pennsylvania
UPPER PALEOZOIC (Upper Ancient Life) Era of Fish and Amphibians	CARBONIFEROUS 115 Million yrs.	Mississippian Pennsylvanian Permian	Age of Coal Age of Amphibians Evolution of Reptiles Maximum thickness of strata, 24,000 feet—in Arkansas; average, 4,500 feet+
	DEVONIAN 50 Million yrs.		Age of Fishes Evolution of Amphibians Maximum thickness of strata, 13,000 feet—in Pennsylvania; average, 3,000 feet
	SILURIAN 40 Million yrs.		Development of Fishes Invertebrates Maximum thickness of strata, 7,300 feet—in Massachusetts; average, 2,000 feet
LOWER PALEOZOIC (Lower Ancient Life) Era of Invertebrates	ORDOVICIAN 110 Million yrs.		Age of Invertebrates Evolution of Vertebrates Maximum thickness of strata, 15,500 feet—in Massachusetts; average, 3,000 feet
	CAMBRIAN 90 Million yrs.		Reign of Invertebrates Maximum thickness of strata, 40,000 feet—in British Columbia; average, 4,000 feet
PROTEROZOIC (First Life)	ALGONKIAN Time probably as long as all of the Paleozoic		Evolution of Invertebrates Maximum thickness of strata, 74,000 feet—in Canada; in Rockies, 37,000 feet
	ARCHAEAN Time not estimated but very long. No known beginning to this division.		Maximum thickness of strata, 74,000 feet—in Canada

Fig. 72. Standard time scale.





sition; and early to middle Tertiary beds found in Western Nevada were involved in this disturbance.

On the theory, advanced in Chapter IV, of the tendency toward the slow creep of magma from beneath the ocean basins to the interior of the continent, as the bulk of the continent is reduced and its weight lightened by erosion, we may frame the working hypothesis that the magma tide which broke out in California and Western Nevada at the close of the Jurassic arrived in Colorado only at the close of the Cretaceous, many millions of years later.

If we consider the whole Cordilleran region and generalize concerning its history, the Tertiary revolution is undoubtedly the greatest which has occurred since the pre-Cambrian. And we must not forget that we are now living in this great period of crustal revolution. In many parts of the Cordilleran region volcanic action and faulting is still persistently going on; and quite certainly ore deposition is taking place at the favorable depths, to be revealed millions of years hence, for a now unknown type of world denizen.

If we take the pre-Cambrian history of the world into consideration we may express the view that the three greatest discernible revolutions recorded were, first, that between the Archæan and the Algonkian (both pre-Cambrian age-divisions); second, that between the Algonkian and the Cambrian; and finally the post-Cretaceous revolution, the extension of which is still going on. The student of geology, if there be any a hundred million years from now, will draw a definite datum of vast unconformities, erosion, and other geological breaks below all the pile of rocks which shall be accumulated over this portion of the world's crust for the next hundred million years; and the significance of that break will appear to him as the Algonkian-Cambrian break appears to us. We are now living in a period of high mountains, glaciers, volcanoes, rapid deposition of rocks—many of which will consolidate as "red beds"—and, as I have above remarked, certainly ore deposition in depth; and these conditions are not confined to the Cordilleran region of North America, but characterize large parts of South America, Europe, and Asia as well.

Summarizing the post-Algonkian magmatic history of the North American continent, it may be stated that during the Paleozoic, both the present Pacific Coast and the present Atlantic Coast were established as magmatic provinces, with all that the term implies, including igneous invasions, ore deposition, and the folding and faulting of rocks. In the Appalachians, the early Paleozoic was the principal period of ore deposition: deposits of gold, chalcopyrite, and pyrite, as well as the ores connected with pegmatites, such as molybdenite, monazite, etc., were deposited from Nova Scotia to Georgia, probably at very considerable depths (perhaps several miles), for the post-Paleozoic erosion has been enormous.

At the close of the Paleozoic the intense folding of the Appalachian mountain belt took place, with the distribution and shape of the folds indicating a thrust from the Atlantic—that is, from the southeast. Subsequent to the

Paleozoic, came the deposition, in the Triassic, along the Atlantic border, of red sandstones like those in the Cordilleran region, indicating rapid erosion of high Appalachian mountains, just as the corresponding red sandstones of Colorado indicate rapid erosion of high mountains uplifted at the same period in or near Colorado. At the close of the Triassic, along the Atlantic border, and just at the eastern base of the main post-Paleozoic Appalachian zone of intense folding, copious intrusions of basaltic rocks took place, in dikes and sheets in the Triassic sandstones. This igneous epoch was accompanied by some ore deposition, especially of copper, as in New Jersey, but no folding of importance; but was followed by faulting such as usually follows igneous intrusions, and is due to readjustment of the position and bulk of the rocks on the cessation of migration, and on cooling. Indeed, there has been little folding, since the close of the Triassic, between the Atlantic Coast and the Rocky Mountains.

On the Pacific side of the acute, nearly right-angled triangle formed by the Atlantic and Pacific coasts there were also early Mesozoic volcanics, whose relations to folding and ore deposition are somewhat obscure. Then we arrive at the period of major revolution which occurred about the close of the Jurassic and the beginning of the Cretaceous in the Pacific coastal belt, and was marked by the intrusion of great masses of monzonitic rock into California and Western Nevada, the uplift of the Sierra Nevada, much folding and faulting of the strata, and very important ore deposits, principally of gold and copper. There was no crustal revolution at that period, in the Atlantic coastal province. Still later, at the close of the Cretaceous and the beginning of the Tertiary, came the establishment of the great Rocky Mountain magma province, with the splendid manifestations of the three phenomena—folding and faulting, igneous intrusion, and ore deposition. Again, this is not represented in the Appalachian belt.

Between the Appalachian and the Cordilleran belts, there

lies a third great province—the Mississippi Valley, where the strata have remained nearly horizontal throughout the whole of geologic time since the Cambrian. I should like to group two of these three provinces together for certain reasons—to group the Mississippi-Appalachian province as one which has experienced neither folding of importance nor the important intrusion of *intermediate-siliceous* igneous rocks since the Paleozoic, as contrasted to the Cordilleran province, where intrusion of mainly intermediate to siliceous magma, and folding, have been so conspicuous at intervals ever since the Paleozoic.

In the Mississippi-Appalachian province there were, indeed, at the close of the Triassic (as I have noted above), basic igneous intrusions over a widespread belt, accompanied or followed by some ore deposition, but not by folding, although followed by faulting. And this recalls my previously suggested (Chapter III, p. 182) hypothesis that it is the intermediate and siliceous igneous rocks which possess the most telluric pressure, giving them surgent or intrusive power, and enabling them to thrust the rocks laterally to one side and the other, in their progress toward the zone where they can cool and so separate from the volatile constituents which furnish their principal motive power. This power is, of course, aided by the relatively lighter specific gravity of these intermediate-siliceous rocks, which helps them in rising. The basic magmas, however, are heavier than the overlying rocks, rather than lighter; and, as is well known, contain less of the volatile constituents than the more siliceous magmas. Hence they do not as a rule form explosive volcanoes, but, where they come to the surface, form quiet eruptions, and in places flow strikingly and steadily out of fissures in vast quantities. The expelling force in these cases may be in part transmitted from afar.

West of the Appalachians a line of faults, anticlines, and basic dikes has been traced by various geologists. The assembled literature has been brought to my attention by

Professor J. Volney Lewis.[3] This line runs through New York, Pennsylvania, West Virginia, Kentucky, and Southern Illinois into Southeastern Missouri.[4] (Fig. 73.) The dikes are all very basic—peridotites—and in addition contain in common certain minerals which make it certain that they all represent a single highly specialized magma. Over 300 miles southwest of the western end of this line, in Pike County, Arkansas, an isolated intrusion of the same magma occurs. The age is here post-Cretaceous, and is considered by those who have described it as probably immediately post-Cretaceous.[5] I personally assume a like age for the intrusion of similar dikes in Kentucky, Southern Illinois, and elsewhere along this line. The period of their injection, therefore, corresponds with the major magmatic period in the Rocky Mountain province, but the magma is quite foreign to the Rocky Mountain region. This line of intrusion and deformation includes a number of anticlinal swellings, such as the Cincinnatian anticline, and the extension of the line westward a short distance strikes the Ozark uplift, which I assume to be (as to its more recent manifestation) of the same general age as the Rocky Mountain uplift.

This means that the forces producing the Rocky Mountain post-Cretaceous uplift, or apparently related to them, affected slightly the whole Mississippi basin, as far as the Appalachians at least, and among other things produced, or at least coincided with, a major line of faulting and doming, over a thousand miles in length, curving from northeast-and-southwest in its passage from New York to Kentucky, to nearly east-and-west in Kentucky, Illinois, and Missouri.

That the intrusive force in the belt of basic dikes under consideration was nicely balanced with gravity and tem-

[3] Gardner: *Bulletin Geol. Soc. Am.*, 1915, Vol. XXVI, pp. 447-483. Kemp and Ross: *Annals N. Y. Acad. Sci.*, Vol. XVII, 1906-7.

[4] Southeastern Missouri, according to Buckley, "Types of Ore Deposits." Edited by H. F. Bain, San Francisco, 1911, p. 104, footnote. Also Sydney H. Ball, personal communication to me, 1922.

[5] Branner and Brackett: *Am. Jour. Sci.*, Vol. XXXVIII, 1889, p. 50.

Fig. 73.—The Eastern United States, showing a chain of occurrences of post-Paleozoic peridotite dikes (×). Data taken from Kemp and Ross, Ann. N. Y. Acad. Sci., Vol. XVII, pp. 509–18, 1907; J. H. Gardner, Bulletin Geological Society of America, Vol. XXVI, pp. 477–83, 1915; also personal communications by J. V. Lewis and Sydney H. Ball. Dikes in Missouri are from published notes by Buckley and unpublished notes by Ball. The location shown out of line, in the southwest, is the Arkansas (Pike County) diamond-bearing peridotite, which is post-Cretaceous and gives a presumptive post-Cretaceous age to this whole dike series. Line of — — — represents a line of structural disturbances—faults and uplifts—taken from above sources. The line in Missouri is the main axis of the Ozark uplift, according to Missouri and United States Geological Survey geologists. The shaded area in Southeastern Missouri is the Southeastern lead and zinc region, containing, also, cobalt, nickel, and copper. Farther west, along the line of disturbance, is the Southwestern lead and zinc region, in which is Joplin. Ore deposits are associated with one of the peridotite dikes in Southeastern Missouri, noted by Ball, and with some of the peridotite dikes in Kentucky. I have simply assembled the data on this map, but they suggest the ores of Missouri—lead, zinc, copper, cobalt, nickel, barytes, and fluorspar—as associated with and generally connected with a post-Cretaceous invasion of a widespread peridotitic magma.

perature, with no excess motive power, is suggested by the case of the dike reported to me in one of the fluorspar mines, which stopped before it reached the surface, but was uncovered by mining. This also explains why igneous intrusions are rare in this Mississippi province. Only along a line of rupture such as this great line of dislocation (over a thousand miles in length), was the temperature, and release of pressure perhaps, sufficient for the right degree of fluidity, and the coincident fissuring available to reduce the ascensive power necessary. This line runs parallel to the Appalachians and the Atlantic Coast in the eastern portion, and in the western portion turns and runs parallel to the long north shore of the Gulf Coast. The faulting amounts in places to as much as a thousand feet, the uplift being on the south-and-east side. Does this mean an uplift of the block on the south-and-east, or a sinking on the north-and-west? It will be noticed that this curve coincides not only with the coastal elements noted but also partly with the curve of the ancient geosynclinal area of the Great Lakes, and even with the curve of the pre-Cambrian land mass which lay just north of the Great Lakes. It, therefore, follows primitive features of crustal structure and heterogeneity.

A reply to our question is perhaps indicated by a consideration of the uplift, on the Atlantic and Gulf coasts, of the Cretaceous and the early Tertiary strata, which took place about the middle of the Tertiary period. The line of faulting appears to have been in general contemporaneous with this coastal uplift, and, therefore, to have assisted in the elevation of the block between it and the coast. And this, as noted above, was in general synchronous with an active period of elevation of the Rocky Mountains and the region further west and south. The block to the north and west of this line of faulting, therefore, probably tended to resist the general uplift, perhaps on account of its superior specific gravity. This resistant area is essentially part of the province of the Great Lakes, which has always been a relatively

depressed area, or what Mr. Bailey Willis has called a negative or heavy element in the crust.

Highly significant is the occurrence along this fault line of very abundant and valuable deposits of barite, fluorite, lead, and zinc, with some cobalt and nickel, these being sometimes closely associated with the dikes. A post-Cretaceous (Tertiary) period of important mineralization, corresponding in age to that in Colorado, and extending over a considerable part of the Mississippi Valley, is, therefore, suggested. This Mississippi province is, however, a magmatically distinct one, as is evidenced not only by the very basic character of the igneous rocks but by the occurrence of nickel and cobalt in some of the ores. I shall discuss this further on.

The combined Mississippi-Appalachian province, therefore, which lies between the Rocky Mountains and the Atlantic Ocean, has exhibited igneous intrusion only twice since before the Mesozoic—east of the Appalachians, at the close of the Triassic, and west of the Appalachians, after the close of the Cretaceous. At both these periods, the igneous rocks were entirely very basic, and were extremely basic in the latter manifestation. A region like the Mississippi Valley, which has remained fairly static and low-lying since the beginning of the Cambrian, is on this account alone indicated as underlain by basic magma; for gravity measurements of the crust indicate that such areas are underlain by heavier rock than are the elevated land areas. The inferred post-Paleozoic extension of this basic area to the Atlantic, as indicated by the post-Triassic diabases, involves the conclusion (based, of course, upon my general hypothesis) that although in the Paleozoic a wave of siliceous magma came in from beneath the Atlantic, the subcrustal magma has been basic ever since. We can only infer that the basic magma is the normal one for this region.

Since the ocean basins are, according to gravity measurements, also underlain by heavy rocks or basic magmas, we must conclude that the waves of siliceous-intermediate

magma which pass from under them to the continents, to support the latter and tend to retain them in isostatic equilibrium, are not typical of the suboceanic magmas, but are, indeed, the lighter and more volatile portion of those magmas, segregated by their lighter specific gravity and buoyant volatile elements—may, indeed, be called the froth of the terrestrial magma, which, tending to rise and move, seeking freer outlet, is drawn off, after accumulation has accomplished a certain volume and pressure, to the continents. Such waves carry with them, as we have seen, the causes for ore deposition of the first degree of magnitude. But the basic provinces, such as this Mississippi basin province, which perhaps may be conveniently visualized as a section of the ocean bottom caught in a wedge and upheld between the Atlantic and the Pacific thrusts of the intermediate-siliceous magma waves, are evidently not without their own great potentialities for ore deposition, and also result in deposits of the first magnitude.

The conceptions which I have outlined in this and earlier chapters seem to me to harmonize with the recorded partly synchronous phases of elevation in different continents surrounding an ocean. The clearest example is the volcanic belt—the circle of fire—which girdles the Pacific. Not only in the western belt of North America has there been a magmatic province during the Tertiary, but on the margin of South America, Asia, and Australasia; all around this belt similar lavas (on the average, intermediate, although showing many more basic and more siliceous derived phases) have been thrown out. Most recent, around the very margins of the great ocean, are volcanoes ejecting mainly hypersthene andesite, and many of these are active. Apparently the subcrustal conditions beneath the ocean may reach the critical stage where flowage landward is set up, all over the oceanic basin at the same time. That different ocean basins, however, are far from synchronous in these magmatic phases is shown by the difference in history between the Cordilleran and the Appalachian provinces of

North America. Please observe, however, that the history of the Pacific belt of North America corresponds with that of South America; and the eastern part of North America has a general resemblance in history to the eastern part of South America.

Reverting to the major uplift stages since the Cambrian, in the Cordilleran region, I have shown that the last two—the post-Jurassic and the post-Cretaceous—were connected with ore deposition. The first and earliest of these major uplift stages—the late Paleozoic early Mesozoic (or Permian-Triassic)—however, although not a period of folding, intrusion, and ore deposition in Colorado, was nevertheless the greatest general uplift that had occurred in Colorado since the pre-Cambrian, and, with the exception of the post-Cretaceous upheaval, the greatest of all post-Algonkian geologic time. Was there somewhere, in this Cordilleran province, intrusion and ore deposition at this epoch also? On the Pacific Coast there seems little available data to enable us to discuss this question accurately; although in general we are aware that these activities did take place. J. R. Finlay has surmised that the important copper deposits of Bisbee, in Arizona, belong to this period. They are later than the Pennsylvanian (upper Carboniferous) and earlier than the Cretaceous. Therefore, they do not belong to the Coloradoan or third (post-Cretaceous) period of mineralization, but they may belong to the second or Californian (post-Jurassic) period. But there is evidence at Bisbee of a long period of erosion before the deposition of the Cretaceous, which would strengthen Mr. Finlay's surmise that the ores may belong to the late Carboniferous early Mesozoic or "Permian" revolution. The Bisbee ores occur in connection with an intrusive mass or batholith of granite porphyry into Paleozoic strata, principally limestones.

In Europe the corresponding (Permian) period of uplift was accompanied by extensive mineralization. This period is called, in Europe, Hercynian. Mountain chains were

uplifted and granitic rocks intruded; and in connection with these are now found deposits of tin, lead, zinc, copper, and silver, in England, France, Saxony, and Spain, according to De Launay.

The newest belt of volcanic activity and earthquake action (late Pliocene-Pleistocene) all along the Pacific Coast, not only of North America but the other continents bordering the Pacific, indicates a fresh wave of magma from under the Pacific, which has not reached beyond its very borders. It is not exhibited far east of California—not, for example, in Eastern Nevada, Utah, or Colorado (I take this belt as a sample cross-section). Possibly the Pliocene uplift of all this Cordilleran region, including the Great Basin, the Colorado Plateau country (leading to the erosion of the Grand Canyon of the Colorado), and the Pliocene uplift of the Rocky Mountains in Colorado may have been due to a transmitted pressure from this newest magmatic invasion.

Recent basaltic eruptions occur in the depressed trough which flanks on the east the Sierra Nevada, which I have called in a previous chapter (Chapter IV) the Sierra Nevada back-trough, and also further east. They usually take the form of small isolated cinder cones of olivine basalt, such as that near Silver Peak, in Nevada, and along the east base of the Sierra block, in California. Many of them are situated, as in the last case named, along strong fault fissures. Similar occasional cones are situated along fault lines in the Colorado Plateau. In Arizona rather more extensive patches of basalt of this recent age occur, as well as recent cinder cones. In Alaska, flows of olivine basalt of relatively recent age, with the craters sometimes quite fresh, as on St. Michael's Island, extend for a thousand miles northwesterly, from Miles Canyon to St. Michael's.[6] These occasional very minor outbreaks of olivine basalt are contemporaneous with the mighty eruptions of (chiefly) hypersthene andesite in the main volcanic belt near the coast.

[6] J. E. Spurr: "Geology of the Yukon Gold District." *Eighteenth Ann. Rep.*, U. S. Geol. Surv., p. 249.

Possibly, also, the great basaltic lava flows of the Columbia River in California and Oregon belong in this group, although, as pointed out by Iddings, they are in part andesitic in character.[7] In general, these olivine basalt eruptions represent sudden emissions of gases and cinders from an underlying olivine-basalt magma, but no strong or sustained volcanism; while the flows, although they may be extensive, seem to have mainly quietly welled out of fissures. In other words, there is small evidence of much telluric pressure, such as bursts through and thrusts aside other rocks: the lava usually selects for its vent positions at the lowest altitude, and avails itself of the channels offered by deep-reaching fault fissures. Quite different are the phenomena of the coastal belt, which obtained during the same period, where in the Cascade range and further north along the Alaskan coast are giant volcanoes whose present activity, as best shown in Alaska, involves the violent shoving up of volcanic islands, great changes of elevation, and earthquakes.

This Pliocene-Recent magmatic province on the Pacific Coast is accompanied by deposits of mercury (mainly the sulphide cinnabar) in California; probably the Alaska (Kuskokwim River) deposits are of the same age. As stated in Chapter XI, mercury seems the most volatile of the elements of the ore magma: it seems to ascend furthest up into cool rocks before deposition, and to deposit at the lowest temperature, near the surface. At Steamboat Springs, in Western Nevada, it is being actually deposited from ascending hot waters, at a temperature of perhaps around 100° C. It is likely that ore deposits belonging to the deeper zones have certainly been deposited and are being deposited during this Pliocene-Recent magmatic epoch, and will be revealed by erosion millions of years from now, for the use of (to our conceptions) almost infinitely remote dwellers on the earth.

From the above consideration of epochs of ore deposition,

[7] J. P. Iddings: "The Problem of Volcanism." 1904, p. 120.

or metallogenetic epochs (the conception and the term both were first suggested by De Launay), it will be seen that while metallogenetic epochs are recurrent and periodic, they are not regular or rhythmic. They depend on a complex of factors yet to be fully enumerated and quantitatively evaluated. These factors begin with original or inherent crustal heterogeneity, and include the universal gradual disengagement of lighter and more volatile elements outward from the underlying world substance, the work of erosion and deposition, the varying resistance to fracture, transmitted stress, and many other elements. Added to all these are the considerations which will be described in the next chapter under the head of Metallographic Provinces.

Enough has been presented, however, in the present chapter, to show how a given metallogenetic epoch may be represented in many parts of the world, and yet be very far from universal; and how the ore deposits of a given metallogenetic epoch may show a resemblance everywhere, due partly to their derivation from the same magma wave and partly to the relative remoteness of age. The last-named factor determines that a very recent metallogenetic epoch, like the last one of the Pacific Coast, shall show only the most superficial (quicksilver) zone of metallic deposition; while a very old one, like that of the Appalachians, will show almost exclusively the deeper zones, like the pegmatitic veins, the gold-quartz veins, and the copper and pyrite ores; and a metallogenetic epoch of intermediate age, like the post-Cretaceous epoch in the Rocky Mountains, will show prevailingly the intermediate zones—those of lead and zinc.

The depth of erosion, and the ore zones exposed, depend, of course, not only on time but on speed of erosion. For example, the Paleozoic pegmatitic veins, the gold-quartz veins, and the copper veins of the Appalachians show the same range of ore-deposition zones as the corresponding veins of the pre-Cambrian in the old pre-Cambrian land of Canada: such, for example, as those in the district in

Northern Manitoba which I have described in Chapter II. If the veins in these two regions were formed at approximately the same depth—and this appears to me a fair tentative assumption—then the total net erosion from the Archæan land of Canada since some stage of the pre-Cambrian has been the same as that from the bolder Appalachian chain since some time in the Paleozoic. Moreover, the gold-quartz and copper veins of the Sierra Nevada are of nearly the same zone of ore deposition—or only a little higher; so that again a corresponding amount of net erosion has taken place in that region since the close of the Jurassic, testifying eloquently to the sustained height and active erosion of the Sierra.

Similarly, post-Jurassic copper ores of the Copper River basin in Alaska represent about the same stage and perhaps approximate depth of ore deposition as those of the Keweenawan (pre-Cambrian) in Michigan, and the post-Triassic in New Jersey, showing again the same relative ratio of erosion as above noted, for the Mississippi-Lake, the Appalachian, and the Pacific provinces. On the other hand, the post-Cretaceous lead-and-zinc deposits of Missouri show about the same stage of erosion as deposits of the same age in Colorado, Utah, and Nevada, as at Leadville, Park City, and Eureka. This at first is somewhat surprising, considering the higher and more mountainous situation of the western deposits; on the other hand, the average rainfall in Missouri has probably been greater than for the Western states.

The net depth of erosion, determining the zone of ore deposition which will be reached after a certain period of erosion, is determined partly by the factor of interrupting sedimentation, and the later removal of such new sediments by erosion. This delays the ultimate erosion by the time necessary for the two stages of the interruption (for sedimentation and for erosion) and the getting back to the surface where the interrupting episode began.

At Georgetown, in Colorado, as I have remarked in

Chapter VI, it is indicated that erosion has removed more than 5,000 feet since the ore was deposited; and in Aspen and in Leadville it may be twice that amount. If these were really formed at the same period as the Missouri deposits and under the same conditions of temperature, and at about the same distance from the surface, the inference is that the exposure of approximately the same relative zones of ore deposition at the surface now indicates the removal from the Missouri area of approximately the same overlying column of rock by erosion: in other words, that the lead and zinc deposits of this region were deposited beneath, let us say, 5,000 feet of rocks which have been since removed. This at first sight conflicts with conditions in Missouri—certainly with commonly accepted conditions. It has been assumed that the conditions were "not very different from those prevailing at the surface."[8] There is, however, nothing in the character of the ores to demonstrate this. Aside from the presence of silver, the metallic minerals—galena and blende—are like those at Aspen and similar Cordilleran districts.

The usually given and accepted explanation for the Mississippi ores is that the ore deposits have been concentrated from minute quantities of the metals originally disseminated (by sedimentation) in the Paleozoic strata. Which stratum was the original source is a matter of wide divergence of opinion among the writers on the subject; also, whether the waters which accomplished the concentration were ascending or descending. The general theory, of course, calls for descending waters; but in various places the evidence of deposition by ascending waters is so strong that an artesian circulation of the ground waters has been postulated—first descending, then ascending to deposit. At Flat River, Missouri, where I have observed these abundant sulphides, the occurrence of the ores mainly below impervious shale beds indicated ascending solutions; and this ore horizon is separated from the underlying pre-Cambrian granite and

[8] Waldemar Lindgren: "Ore Deposits," 1919, p. 446.

porphyry by only 200 feet of sandstone. Certainly, the solutions in this district rose up through the pre-Cambrian rocks; and the likelihood of a similar source for other districts is strong. Traces of lead and zinc in the Paleozoic limestones of this region have been found, but rather less than more than the average for rocks in general, especially igneous rocks. The ground water of this region has also been found to contain zinc, which, indeed, is to be expected, with the amount of zinc which has been deposited in the strata, and which these waters traverse. Such traces can doubtless be found in the waters of any mining region.

Some of the geologists who thus assume the concentration of the ore deposits from the Paleozoic sediments have believed that the concentration was effected at the time of the deposition of the Carboniferous beds, by some process which I cannot guess; others believe that the concentration was post-Carboniferous.[9] As for myself, I have in the early part of the chapter indicated my belief that the ores are post-Cretaceous.[10]

How much erosion has there been in this region since the Cretaceous?

[9] C. E. Siebenthal: "Origin of the Lead and Zinc Deposits of the Joplin Region." Bulletin 606, U. S. Geol. Surv., 1915.

[10] Sydney H. Ball gives me the following note, after the above was written. His note is based on a brief examination made in 1922:

"In southern St. Genevieve County, approximately 18 miles southeast of Flat River, is the hamlet of Avon. About a mile north thereof, in Section 2, Township 35, Range 7, is the Vogt farm, on which is a peridotite pipe somewhat less than 200 feet in diameter. This is presumably of Cretaceous age, and is to be correlated with the basic dikes of Southern Illinois. The peridotite is intrusive in the Bonne Terre limestone, and has metamorphosed same for from 10 to 20 feet from the periphery to a dense flinty, siliceous limestone. At one point on the contact is a shallow prospect hole. Here the metamorphosed limestone has been intensely shattered, and in it are stringers, in part largely parallel to the bedding but partly crossing same, of galena, zinc blende, pyrite, marcasite, and chalcopyrite, together with considerable calcite. The ore minerals are largely confined to the limestone, although they also occur to a limited extent in the igneous rock.

"The data are insufficient to definitely prove the origin of these ore minerals. On the other hand, those familiar with our Western ore deposits

That part of the Mississippi Valley which includes the lead and zinc region of Missouri has been above the sea and has been worn down by the Mississippi and its tributary streams, so far as is known, since the close of the Paleozoic—no Mesozoic and only minor Tertiary strata occur.

At Flat River, I have noted (Chapter VIII) a fault of 500 feet vertical displacement, belonging to a series of post-mineral faults (which cut the ore), which has been entirely subdued by erosion, so that one side, at the surface, is no higher than the other. To arrive at the present level, therefore, the block on one side of the fault (representing, since there is no other fault near by of like magnitude, the whole country on that side of the fault) must have been worn down 500 feet further than the other, and all since the ore deposition. But while the uplifted side was being worn down, the other was being worn down too: the 500 feet simply represents the relatively small difference of erosion rate. I do not know how great this excess rate may have been, but as a guess I should say that it could not have been more than 10 per cent of the total rate of erosion; and if this is assumed, then 5,000 feet of strata must have been eroded before the two sides became even. Assume any relation you like, and you still have the result of several thousand feet of erosion since ore deposition.

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would, I think, without much hesitation, consider the origin of the ore minerals more or less as follows:

"1. Intrusion of the peridotite pipe, accompanied by metamorphism of the limestone.

"2. Shattering of the limestone, due to readjustment after igneous intrusion.

"3. Deposits of ore minerals by waters derived from the cooling igneous mass.

"While by no means a proof of the origin of the orebodies of the Southeast Missouri lead district, the deposit is certainly a most suggestive one."

I have seen the specimens gathered by Mr. Ball at this locality. In the predominant sulphides, and the calcite gangue, with the (apparent) lack of quartz, the deposit falls in line with criteria I give in Chapters XII and XIII as characteristic of the basic-magma-derived sulphides.

The ore deposition, as I have noted in Chapter VIII, took place at a definite epoch, after the initiation of strong fracturing in the district, which gave access to the mineralizing solutions; these, therefore, deposited their metals, along these fissures, in beds whose composition favored selective precipitation, producing the definite oreshoots, which are called "runs" in Missouri; and subsequent development of the fissures took place after the ore deposition, and produced the post-mineral faults. As for those who believe that the ores have been deposited by circulating ground waters, I should like to have them observe, as I did, the ores underground at Flat River, and assure themselves that the copious waters which circulate along the post-mineral faults have produced no noticeable rearrangement of the abundant and massive ores: then reflect only on the time that it took one of these faults to be subdued by erosion. The 500-foot fault mentioned above would certainly take a minimum of 500 times 5,000,[11] or 2,500,000 years, for its effects to be subdued by erosion, so that the rocks on each side are worn down to a common level. Then I should like to have them tell me how long it would take for such ordinary ground-water solutions to deposit these ores. Although, as I said above, I cannot evaluate the slight work of the post-fault waters (because I noted no work whatever), if we take the ratio of 1 to 1,000,000 at a hazard, as the difference between pre-fault and post-fault ore, we would have 2,500,000,000,000 years for the orebody to form. If we take only a ratio of 1 to 1,000, which is absurd in its smallness, we have a time space of 2,500,000,000, many times more than the whole estimated space of geologic time since the beginning of the Cambrian. But if we adopt the method I used at Aspen (Chapter VIII, p. 360), and note that the ore deposition took place after the initiation of the fault fissuring, but before the post-mineral faulting, and estimate the movement during ore deposition (it has not, I

[11] See Chapter VIII, p. 340. The Mississippi basin is being lowered at the rate of about one foot in 6,000 years.

think, really been noted, so small is it) at 1 foot, with the total post-mineral movement at 500 feet, we have a period of 60,000 years for the ore deposition.[12] This, I believe for the reasons stated above, is too liberal; but the broad conclusion, as at Aspen, is that the time interval of the ore-deposition period lies in the tens of thousands of years or less.

There is one district which I must mention while I am on this subject, and yet I do so with hesitation, on account of my insufficient knowledge and the wide discordance of the testimony. That is the Arizona copper region. Here in a relatively small area, comprising the southern half of Arizona, with adjacent Western New Mexico and Northern Sonora, is the richest and most productive copper district thus far discovered in the world. Taking 1916 as an example, I find that the listed production from districts in this little area (excluding Sonora) amounted to 41 per cent of the production of the United States, which in the same year amounted to 62½ per cent of the world's production. This little area, therefore, produced over 30 per cent of the copper produced in the world! It is not more than 400 miles in diameter, or around 4 per cent of the area of the United States, and three-tenths of 1 per cent of the area of the land in the world! Therefore natural processes appear to have produced a far greater concentration of copper in this little mole on the face of the earth than anywhere else.

There are other remarkable copper districts whose discussion is bound up with this, the archtype. Therefore we must be quick to study the causes of so egregious a drawing together of copper from its usually widely disseminated

[12] Arrived at, in this case, as follows: take Barrell's estimate (see p. 396) of Tertiary time, at 60,000,000 years. The ore deposits, as I have shown, are probably post-Cretaceous: a mid-Tertiary age would make the time since the inception of the faulting and the ore deposition 30,000,000 years. The time interval per foot, estimated on the 500 feet of faulting, would then be 60,000 years. Even by varying the assumed figures greatly, results of the same general order of magnitude are obtained. My argument here is, of course, much looser than in the Aspen case, since I did not observe whether or not there was ore deposition along the 500-foot fault, although I did observe it in the path of lesser faults.

occurrence in the earth's crust. Has it been due to the action of atmospheric waters—rains sinking in, dissolving out the traces of copper which (like lead and other metals) exist in all rocks, carrying them to some location, channel, fissure, or bed favorable for precipitation, and there depositing, point by point, till the bonanzas and enormous "disseminated porphyries" have been formed? "Ah, no," my reader will say; "this does not explain why Arizona produced 30 per cent of the world's copper. It has not and never had 30 per cent of the world's water or 30 per cent of its rocks for leaching purposes." Not more inadequate, however, than the same explanation as applied to the lead and zinc deposits of Missouri and the copper ores of Lake Superior—and for the same kind of reasons, if for no other, that you have given. In this Arizona metallographic province, however, we luckily do not have to argue the question —all agree as to the genetic connection with igneous intrusive rocks (are they not there to see!), and most acknowledge in this connection the evidences that the solutions which originally deposited the copper, at least in most of these districts, were of magmatic origin.

My own studies in this region consist of geological surveys in the Ray and Helvetia districts, in Arizona, and brief examinations and reconnaissances at Globe and some minor districts in Arizona and New Mexico. I have referred several times before to my work at Ray and at Helvetia (Chapter VII). At Helvetia, the ores occur in connection with intrusions of granite into limestones of Paleozoic age, and intrusion and ore deposition are earlier than a series of red conglomerates and sandstones which probably correspond to those described at Bisbee (which is only about 50 miles away) by Dr. Ransome,[13] which he has assigned to the lower Cretaceous, on the basis of fossils found in conformably overlying limestone. As the limestones in this Helvetia region, judging from those which have been determined in

[13] "Geology and Ore Deposits of the Bisbee Quadrangle, Arizona." By F. L. Ransome. *Professional Paper* 21, U. S. Geol. Surv., 1904, p. 70.

near-by Arizona districts, are partly Carboniferous, including the Lower and Middle Carboniferous (Pennsylvanian), the ore deposition was post-Carboniferous and pre-Cretaceous, which fixes it as somewhere in the lower Mesozoic. In Bisbee, according to Dr. Ransome, the same conditions obtain. Jurassic and Triassic strata are probably entirely absent; but a great period of erosion intervened between the period of ore deposition and the deposition of the Cretaceous rocks, and thousands of feet of strata were stripped off in the pre-Cretaceous interval, exposing the granitic and coarse porphyritic-textured rocks and the relatively deep-seated copper zone of ore deposition at Helvetia and at Bisbee. At Bisbee there is also a great unconformity accompanying the erosion period, and very likely at Helvetia, too. When we consider, further, that at Helvetia the copper ores are associated with the development of lime silicates in the limestones which have been intruded by the granites, it is seen that a definitely great thickness of overlying rocks has indeed been removed since the period of intrusion, lime-silicate formation, and ore deposition, theoretically at least (since the copper zone underlies the lead-zinc zone) greater than the 5,000 to 10,000 feet which I have reasoned has been removed from above the lead-zinc deposits of Colorado since their deposition. If we postulate roughly the original depth of copper deposition as three miles, or 15,000 feet (see p. 293), then at the rate of erosion of a foot in 5,000 years (see p. 340) the erosion interval represents a time interval of erosion and ore deposition, of some 75,000,000 years; in other words, the ore deposition antedated the Cretaceous by an immense period, of which this figure is an index. According to Barrell's estimate of geologic time, the duration of the Triassic and Jurassic, or the gap between the Permian and the Cretaceous, was 80,000,000 years. The coincidence of these figures, which I am willing to grant is fortuitous, was not premeditated—the figure of 75,000,000 years was written

down some days before I had access to Barrell's estimate—so I leave it as it stands.

This Arizona copper region, which we are considering, lies a matter of five or six hundred miles southwest of Central Colorado, for which region I have outlined the sedimentation and oscillations, as a type of Rocky Mountain history. In the Aspen district we find strata which bridge, in part at least, the gap between the Carboniferous limestones and the Cretaceous; these strata are red sandstones which have been referred to the Permian and the Triassic, followed by Jurassic beds. The estimate of the thickness of these beds at Aspen is around 7,000 feet. These red sandstones, then, represent the period of erosion in the Arizona district, as exemplified at Bisbee and at Helvetia.

In tracing the history of uplifts in the Aspen region, I have shown that the first great uplift since the pre-Cambrian took place in the Permian; and that this was the greatest uplift of all uplifts from the pre-Cambrian to the present, with the exception of the post-Cretaceous uplift, in which Colorado was for the first time in its history a magmatic province, whereas the Permian uplift was not marked by igneous intrusion, folding, or ore deposition. The magmatic province of this period was, then, partly at least, in Arizona.

Reverting to Bisbee and Helvetia, all these considerations show that the epoch of ore deposition (which was, of course, and as a conclusion resulting from all investigations, part of the threefold phenomena of folding and uplift, igneous intrusion, and ore deposition) could not possibly have been that late Jurassic early Cretaceous period so prominent in the Sierra Nevada and Western Nevada, but belonged to the Permian revolution, so conspicuous over the world. This is also Dr. Ransome's impression;[14] and is, moreover, the opinion of Mr. J. R. Finlay;[15] while Mr.

[14] *Op. cit.*, p. 160.

[15] "Cost of Mining," Third Edition, 1920, p. 248.

Waldemar Lindgren is inclined to refer it to the Jurassic,[16] without, I believe, giving full consideration to the great erosion interval. There are other deposits of this period in this province, such as Silver Bell,[17] near Tucson, in the same general region as Bisbee and Helvetia; and probably a number of other important ore districts, which I shall not now inquire into, as I am far from wishing to make an exhaustive examination into all of the many interesting and important districts of this province, but purpose only to inquire into certain outstanding principles.

Let us then consider next the camp of Clifton-Morenci, in Arizona, about a hundred miles due north of the camps I have been discussing. Here, according to Mr. Lindgren,[18] who has made a monographic study of the district, a stock of granite porphyry and quartz monzonite porphyry breaks upward across pre-Cambrian granite, about a thousand feet of overlying Paleozoic rocks, and Cretaceous sediments which are 400 feet thick. This intrusion, it will be observed, has leaped the unconformity and erosion interval between the Paleozoic and the Cretaceous, and is, therefore, representative of an entirely different epoch of intrusion from that at Bisbee and Helvetia. Lime silicates have developed in all the formations cut: the orebodies, which are mainly of copper (chalcopyrite), with zinc-blende and occasional molybdenite, occur mainly in the Paleozoic limestones.

This epoch of intrusion and ore deposition probably belongs to the immediately post-Cretaceous (Coloradoan) revolution, like the lead and zinc deposits of Aspen and Leadville, in Colorado, so often referred to, and the copper deposits of Bingham Canyon, in Utah. It will be noted that the Permian intrusive at Bisbee, Helvetia, and Silver Bell is granitic and alaskitic and even arizonitic (see p. 310), while the post-Cretaceous intrusive at Clifton is monzonitic. The monzonitic character of this post-Cretaceous magma

[16] "Mineral Deposits," Second Edition, p. 732.
[17] C. A. STEWART: *Trans.* A. I. M. E., Feb., 1912, p. 455 *et seq.*
[18] *Professional Paper* 43, U. S. Geol. Surv., 1905.

is, indeed, very characteristic wherever encountered: it remains to be seen, on further investigation of the Permian deposits, whether or not the Permian intrusions are also as characteristically granitic-alaskitic.

The Clifton-Morenci post-Cretaceous group is abundantly represented elsewhere. In adjacent New Mexico, for example, Lindgren and Graton[19] have classified numerous ore deposits of this period, mainly in the southwestern corner of the state, but extending therefrom in a definite belt north-northeast to a point east of the center of the north boundary of the state (Fig. 79). Lime silicates accompany the contacts of the intrusive monzonitic rocks of this belt: among the metallic ores copper (chalcopyrite) is predominant, but is usually accompanied by zinc (blende), and in one important district (Magdalena) zinc predominates. The general zone of ore deposition is, therefore, higher (copper-zinc zone) than for the distinctly copper zone of the Bisbee Permian group. Lindgren and Graton find that at the period of this intrusion and ore deposition there was a cover of sedimentary rocks over New Mexico 6,000 to 9,000 feet thick, of which the Cretaceous was 3,500 to 5,000 feet thick. In the sedimentary rocks the monzonitic intrusions spread out frequently in the form of laccoliths, and some of these ascended as far up as the Upper Cretaceous rocks, and hence had a probable cover of only 2,000 to 3,000 feet.[20] Lindgren mentions several mining districts where the ores must have been formed at these comparatively shallow depths. At one of these (Cerrillos), the ores, which Lindgren states were probably deposited under not more than 4,000 feet of strata, are silver-lead zinc, and a little chalcopyrite. "In depth zinc ores are said to prevail."[21] The chief gangue is quartz. In another of these districts (Elizabethtown) the characteristic ores are auriferous pyrite, with a little pyrrhotite, chalcopyrite, magnetite,

[19] *Professional Paper* 68, U. S. Geol. Surv.
[20] Lindgren and Graton: *Op. cit.*, p. 41.
[21] *Op cit.*, p. 167.

etc., and are associated with lime silicates. As a member of this post-Cretaceous group, but representing an occurrence where the intrusives have been inserted at greater depth, into the Paleozoic strata, Lindgren cites the Organ Mountain deposits, where, however, the known facts concerning the intrusion simply denote that it is post-Carboniferous. This district shows copper and zinc near the contacts of a batholith; the lead deposits occur mainly farther away, and the gold- and silver-bearing quartz veins were a later deposit. The Tres Hermanas, also cited as occurring in Mississippian (Lower Carboniferous) limestones, is a lead-zinc deposit associated with lime silicates.

The zones represented by many deposits of this post-Cretaceous group are, therefore, above the copper zone, and include mainly the principal overlying zones as I have defined them (see p. 283), which, in ascending order, are the auriferous pyrite zone, the zinc zone (Magdalena, etc.), the lead zone, the silver zone, and the upper gold zone (see p. 699), in various combinations. The depth of 4,000 feet below the surface given by Lindgren for the silver-lead zone at Cerrillos, overlying the zinc zone, adds valuable data to that which we have already acquired elsewhere (see p. 293, Chapter VI). In general, therefore, these immediately post-Cretaceous ores represent higher zones, and hence shallower depths, than what we know of the Permian ores; and if, according to Lindgren, the former have been deposited at depths of 4,000 to 9,000 feet, we are justified in postulating a greater original depth for deposits like those of Bisbee and Helvetia, just as I have done above.

All, or nearly all, of the post-Cretaceous intrusives described by Lindgren and Graton in New Mexico are associated with the development in the intruded limestones of lime silicates and sometimes other minerals such as tourmaline, which are characteristic of "metamorphism." With these the metallic minerals which constitute the ores are more or less closely associated, and, therefore, these writers have classified all these ores, whether of silver, gold,

lead, zinc, copper, or molybdenite, among the group of "contact-metamorphic deposits." I have earlier pleaded for a chary use of this term. In the present case, and without having the intimate knowledge sufficient to discuss critically, I will simply point out that the general association of metallic minerals with lime silicates and other "metamorphic" (better "metasomatic"—see p. 329) minerals is not necessarily proof or evidence of contemporaneity. Nor does the association of metals with such silicates indicate necessarily a high temperature origin—indeed, unless contemporaneity or a definite relation can be proved, it indicates nothing at all, even when the metallic minerals are found intimately disseminated through the lime silicates. I can illustrate this by referring to the primary metallic sulphides, such as cupriferous pyrite, often found disseminated through an igneous rock, such as the monzonite porphyry, at Bingham, in Utah, and elsewhere—whence the commercial and popular term "porphyry coppers" arose for ore deposits of this type. We know that the component silicate minerals of such igneous rocks crystallize at high temperatures. Does this mean a high temperature for the deposition of the cupriferous pyrite? By no means, you will rejoin: it means nothing at all—there is no known or necessary relation between the temperature of deposition of the pyrite and that of the feldspar, quartz, and mica of the porphyry. Yet it is not so very long ago that the pyrite was held by geologists to be of igneous origin, on account of this association; and, at all events, the analogy with metasomatic ("metamorphic") deposits of lime silicates containing metallic sulphides is excellent. We know, of course, that the intrusion of the monzonite took place at a high temperature, and this is quite sufficient, in point of temperature, to explain the formation of lime silicates and similar metasomatic minerals. But the temperature of deposition of each metallic sulphide is a subject for separate investigation. I offer this suggestion with apologies to the

extremely able geologists who have described the deposits in question.

Altogether, therefore, I feel that the classification of ore deposits by their metals, instead of by the associated non-metallic minerals, is the safe and simple one; although where critical and accurate study of the relation of metallic to non-metallic minerals is possible, it will generally be very fruitful. Normally, however, as my investigations at Matehuala and elsewhere indicate, the ore of the copper zone is deposited at about and below the critical lower limit for lime-silicate deposition, and that only for the deposition of lime silicates of a typical iron-rich kind—hedenbergite (pyroxene), actinolite (hornblende), and andradite (garnet); and the upper metal zones—like zinc, lead, auriferous and argentiferous pyrite, pyrrhotite, and arsenopyrite, silver, and the upper gold zone—were normally deposited at temperatures too low for the formation of lime silicates, but favorable for the development of quartz and calcite. I suspect, therefore, in the case of the "contact-metamorphic" deposits of lead, zinc, auriferous pyrite, etc., which have been reported, that the metallic minerals are younger than the lime silicates and many other characteristic non-metallic minerals with which they are associated: just as they are younger than the primary minerals of the igneous rocks, in which rocks they also occur disseminated or veinwise.

It is possible, of course, in readily conceivable cases, that they may be older than the lime silicates, if a later surgence of the underlying magma should have raised the temperature to that requisite for the formation of lime silicates, and if thus the lime-silicate zone has been superimposed on normally overlying zones of metal deposition. I have shown elsewhere (Chapter V) that the superposition of normally lower zones of metal deposition upon normally higher ones actually occurs not infrequently, for the causes above mentioned. Any ore deposit may thus on occasion, either by a reversal of the trend of the temperature gradient, as above, or by a subsequent and independent ascension of

temperature and pressure, due to quite new causes, be involved in a recrystallization attended by the formation of lime silicates and other characteristic minerals of metamorphism and metasomatism.[22] (Note 22 appears at the end of the chapter.)

There was deposition of copper in this Arizona copper district, not only at the probable period of the Permian revolution and at the period of the post-Cretaceous revolution, but also at a much earlier date—that of the pre-Cambrian revolution, the vastest of the three. The most conspicuous representation of this is at Jerome, scarcely over 100 miles northwest from the post-Cretaceous copper deposits of Ray and Globe, and 300 miles northwest of the probably Permian camp of Bisbee. The situation at Jerome is interestingly discussed by Mr. Finlay in his book on the "Cost of Mining,"[23] and more in detail by Mr. Reber.[24] Mr. Finlay calls attention to the long period of pre-Cambrian (Algonkian) sedimentation, resulting in the accumulation of vast quantities of mud and fine sands, now hardened into shales and fine sandstones. He notes that this long period of sedimentation, when the detritus was eroded from land areas not now exactly known, was without volcanic action or crustal disturbance; but that finally the sedimentary period was terminated by volcanic activity, igneous intrusion, and folding; and the folded rocks, uplifted into land masses, were very deeply eroded before the Cambrian sea again crept across the land and covered the pre-Cambrian strata with the unconformably overlying lowest beds of Cambrian quartzite. The ore deposition, according to the general rule, was the concomitant of the igneous intrusion, the folding, and the uplift. At Jerome the pre-Cambrian rocks are altered lavas and tuffs, cut by quartz porphyry, all more or less schistose; and all these are cut by fresher and unsheared diorite. This sequence of rocks seems to correspond with the pre-Cambrian at Ray, where no pre-

[23] 1920, McGraw-Hill Book Co., p. 201.

[24] *Trans.* A. I. M. E., Vol. LXVI, p. 3.

Cambrian mineralization was noted. At Jerome the ore is associated with the quartz porphyry and is cut by the later diorite; it consists of quartz, pyrite, and chalcopyrite.

The Jerome deposit is not the only pre-Cambrian deposit in Arizona, although the richest. In adjacent New Mexico, there are a number of pre-Cambrian deposits,[25] of which the ores are mainly copper and gold, with zinc and silver. These deposits were principally formed following after pre-Cambrian granitic intrusions. In the Zuni Mountains, the pre-Cambrian, with its ore deposits, is directly overlain by the subsequent "red beds" of the Permian and Triassic.

Finally, copper occurs in this Arizona province at still a fourth period—the later Tertiary, in surface lavas. Such, for example, are described by Schrader[26] in the Santa Rita-Patagonia Mountains in Arizona, in which region lies also the Helvetia district, referred to above, as, like Bisbee, probably Permian. According to Schrader, copper deposits occur in this range in andesite and rhyolite of probably late Tertiary age. They are fissure veins and to some extent replacement deposits, containing principally copper, lead, silver, and gold. The primary ore minerals are (my own arrangement) specularite, molybdenite, chalcopyrite, bornite, chalcocite, pyrite, sphalerite (zinc-blende), galena, argentiferous galena, tetrahedrite, argentite, proustite, and gold. This indicates nearly the whole temperature range of ore deposition. The gangues include quartz, calcite, barite, fluorite, rhodochrosite, and rhodonite. These deposits are believed to have been formed near the surface, but how near is the question. In general, they illustrate the principles discussed in Chapter VI, showing how, in the case of volcanic rocks, where the zones of the elevated temperatures requisite for ore deposition were brought relatively near the surface, and the vertical range of each shortened greatly by the rapid fall of temperature near the surface,

[25] LINDGREN, GRATON and GORDON: *Professional Paper* 68, U. S. Geol. Surv., p. 48.

[26] SCHRADER, F. C.: *Econ. Geol.*, 1917, Vol. XII, No. 3, p. 262 *et seq.*

the ore zones tend to be "telescoped" over one another, and form complex ores representing nearly all the normal ore zones. The rules of more or less orderly and spacious deposition in successive zones, exhibited best where the heat and magma solutions are both caused by the slow intrusion of a batholith in depth, and more sketchily and hurriedly where the heat is supplied mainly by intrusions in the middle depths, become unrecognizable where the heat is raised by volcanic action so that an elevated temperature persists till near the surface—too high for ore deposition—and then the sudden decline of the temperature curve produces a rapid "dumping" of the metals in the ore-magma solutions. The deeper the center of heat and the slower its rise and fall (due to the manner of intrusion of the igneous rock), the better developed and more distinct the ore zones, and the more diagrammatic the exhibition of the law of ore deposition. Conversely, the nearer to the surface the locus of super-ore heat (meaning temperatures too high for ore deposition), and the more rapid the movements of the igneous rock, the more the ore zones tend to be superimposed, and even "scrambled" together.

Now, the remarkable thing about this southern Arizona region is that there are important representatives of four great periods of ore deposition—pre-Cambrian, Permian, post-Cretaceous, and late Tertiary; and that the ore of each period was very predominantly or importantly copper. I do not know of any other so limited district which shows this puzzling circumstance. Is it the explanation that after each period of ore deposition erosion progressed to the approximate plane where the copper zone was chiefly uncovered, and thus that the great abundance of copper in each was due to a fourfold coincidence? I think we can hardly assume that: the other zones of ore deposition are well represented, in various districts, but they are quantitatively not so important as the copper ores.

We must, I think, admit that in all ages, at periods many millions of years apart, igneous-magma intrusion was

accompanied by an ore-magma intrusion in which copper was relatively phenomenally abundant. Another indication of the consanguinity or chemical relationship of the ore magmas at the different epochs is possibly the presence of molybdenite, which has been noted, sometimes conspicuously, in the ores of all of these periods. Arizona, therefore, as exhibited by the products of at least four distinct widely separated metallogenetic epochs, is a metallographic province. And on the subject of metallographic provinces I shall enlarge in the next chapter.

[22] (See p. 424) What I am inclined to believe may be a striking example of this is the unique zinc-iron-manganese deposit at Franklin Furnace, New Jersey, where the ore minerals are exclusively oxides and silicates, with no sulphides, and consist of minerals not known in commercial quantity elsewhere,[22a]—in other words, they constitute an outstanding exception to the rule in ore deposits. Such an exception must be explained by an unusual combination of generally known processes and conditions, and not by a single normal process; for if the latter were the case there would be other similar occurrences known in the world. The ores are chiefly zinc silicate (willemite), with zinc oxide (zincite), and a mixed oxide of iron, zinc, and manganese (franklinite). The unusual character of this occurrence is further emphasized by the presence of many other singular minerals, such as tephroite (manganese silicate); schefferite, or manganese pyroxene (silicate of manganese, iron, magnesium, and lime); gahnite or zinc spinel (zinc aluminate); manganese garnet (silicate of iron, manganese, and alumina); and others not so rare.

In analyzing the history of this unique and as I believe, therefore, plainly compound-processed deposit (that is, due to a combination of two or more generally known and distributed processes) we are fully warranted, I believe, in assuming a primary deposit of zinc sulphide, together with iron in the form of pyrite, and manganese in the form of rhodochrosite or rhodonite or mixed carbonates of manganese, iron, magnesium, and lime. This is a familiar and characteristic mode of occurrence, like that in many districts. The Franklin Furnace ores, as described by Dr. Spencer,[22b] occur in pre-Cambrian crystalline limestone, in one important instance, at least, near and parallel to the contact of a coarse gneiss of igneous origin. Dr. Spencer believes, and I accept his assumption, that the original deposit was magmatic and depended upon the intrusion into the pre-Cambrian lime-

[22a] See, however, my review in *Eng. Min. Jour.-Press*, Oct. 14, 1922, p. 687, of the Monograph on the Broken Hill district, Australia, by E. C. Andrews (1922). Manganese garnet and zinc spinel occur at Broken Hill as at Franklin Furnace. This analogy, however, does not militate against my general argument.

[22b] U. S. Geol. Surv., Geologic Folio 161, 1908.

stone of the igneous rock which has since been transformed into gneiss. The space relation—the apparent dependence of the ore on the original igneous contact—certainly indicates this. Starting with the original form of the minerals which I further assume (deposits of zinc-blende, pyrite, etc., replacing favorable beds in the pre-Cambrian limestone, near the igneous contact), what was the probable subsequent history? The deposits were bared at the surface in pre-Cambrian times by erosion, in substantially the same condition as they are today, for Cambrian limestones, unmetamorphosed, cover the rocks of this area on two sides. The erosion of the pre-Cambrian revolution, therefore, was very deep, and the time interval thereby indicated enormous. Long, long before the Cambrian sedimentation, the igneous rock, the intruded limestones, and the ore deposits had been subjected to heat and pressure, and had been metamorphosed. This is indicated by the transformation of the igneous intrusive into gneiss, while the intruded pre-Cambrian limestone became simply crystalline. This latter circumstance—the absence of the development of lime silicates at the expense of the limestone—suggests metamorphism, not metasomatism: it indicates heat and pressure, not the addition of foreign magmatic material, except for the possibility that heated invading solutions might have been calcic rather than silicic (Chapter XIV). The transformation of the igneous rock into gneiss indicates flowage under pressure and heat, such as, for example, would be due to the slow pushing upward of an intrusive batholith below, and a raising of the temperature therewith. Such a resurgence of heat, with the great indicated pressure, would alter the ore deposits, like the limestone, by metamorphism. Zinc sulphide, iron sulphide, and mixed carbonates of manganese, iron, and lime became silicates and oxides. Sulphur and carbon dioxide were eliminated in order to form new mineral combinations, more stable under the new conditions of heat and pressure.

What warrant have we for the above assumptions? For the increased pressure obtained, the transforming of the igneous rock into gneiss, indicating sufficient pressure to induce flow structure; for the approach from below of a batholith, we have intrusions of pegmatite dikes, which are later than the gneiss, limestone, and ore, and which accordingly betoken an igneous batholith lower down. These pegmatite dike magmas must have arrived at a considerably elevated temperature, for they are believed by Dr. Spencer to have produced secondary metamorphism and to have formed typical metamorphic high-temperature minerals, which are often associated with pegmatite magmas, such as fluorite, apatite, and scapolite, containing characteristic volatile elements. But the pegmatite dikes did not arrive at so high a temperature and pressure, according to our theory, as obtained previously, for they brought with them minor amounts of the normal metallic sulphides, such as zinc-blende, galena, arsenopyrite, chalcopyrite, and bornite. Nor was the subsequent temperature and pressure as great as that preceding, for the pegmatites have not been forced into flowage, nor have their sulphides been metamorphosed.

My conclusion, then, is metamorphism of this ore deposit by a temperature higher than that at which all magmatic sulphide ore deposits

ordinarily form. In previous chapters (Chapters I, p. 80; V, p. 264; VI, p. 297) I have shown that this range of temperature is relatively small, the various successive zones of ore deposition being formed at probable temperatures of from around 575° C. down to a somewhat lower temperature In the igneous magmas, however, the temperatures are much higher—surface lavas, as above stated, have temperatures of probably around 1,000° C., more or less (p. 297); and deep magmas will probably be nearly as hot. Now, it is known that the metals which crystallize in igneous rocks do so mainly as oxides (magnetite, ilmenite, chromite) and silicates (pyroxene, horn-blende, etc.), instead of sulphides, although sulphur is contained in these magmas and is given off from them in large quantities, and at a lower temperature combines most characteristically with the metals, to form the normal type of ore deposits. Therefore, at the usual temperature of magma consolidation, oxides and silicates are formed and sulphides are unstable; and at a much lower temperature, sulphides are crystallized. According to this, the subjecting of sulphides to greatly increased heat and pressure should reverse the sequence, and produce silicates and oxides at the expense of sulphides and carbonates.

This hypothesis seems to be confirmed by certain observations on furnace slags. Willemite, for example, has been observed in such slags, as has been gahnite (zinc spinel), crystallized with tridymite, the high-temperature form of silica,[22c] indicating a temperature above 800° C. (see p. 80). Zincite, also, has been repeatedly observed in furnace slags[22d]. All this renders it extremely probable that the approaching batholithic magma from below heated these ores, and that the metamorphism of the orebodies therefore took place at a temperature perhaps twice as high as that under which they were formed. The later intruding pegmatite magma, however, crystallized (see p. 80) at 575° or less, and under these conditions metallic sulphides were stable, and were deposited.

It is a corollary of the above considerations that sulphide orebodies, even when associated with basic magmas, such as the nickel ores of Sudbury, represent practically the latest stage of magmatic crystallization, and indeed the same stage as the sulphide ores connected with siliceous igneous rocks; and with this conclusion the geological evidence at Sudbury agrees (p. 567). Also, deposits such as are often found near the contact of igneous intrusions, which contain both iron oxides and sulphides (magnetite or hematite and pyrite), show that the transition from the critical higher iron-oxide temperature to the critical iron-sulphide temperature was passed, probably with falling temperature. There are primary oxides of iron, just as there are primary silicates; but primary oxides and silicates of zinc, lead, copper, etc., probably do not occur as separate minerals: these last-named metals seem more volatile, and join with the sulphur in escaping from the primary magma. The occurrence at Franklin Furnace is, accordingly, probably secondary. We may have secondary magnetite or hematite also thus formed, as is well known.

Therefore, magnetite orebodies may be either primary or secondary;

[22c] Dana: "System of Mineralogy," Sixth Edition, 1896, p. 461.
[22d] *Op cit.*, pp. 209, 1053.

although chromite, so far as known, is primary only. I doubt, however, if even these primary oxides, connected with the magmas, whether in them as crystals or formed on their borders or in the invaded rocks, always or even generally represent an early crystallization of the cooling magma. There is much evidence to indicate that they are frequently a late crystallization, and that, in common with the silicates high in iron, they are followed immediately by the sulphides. All are, therefore, part of one general process, and represent stages characteristic of falling temperature.